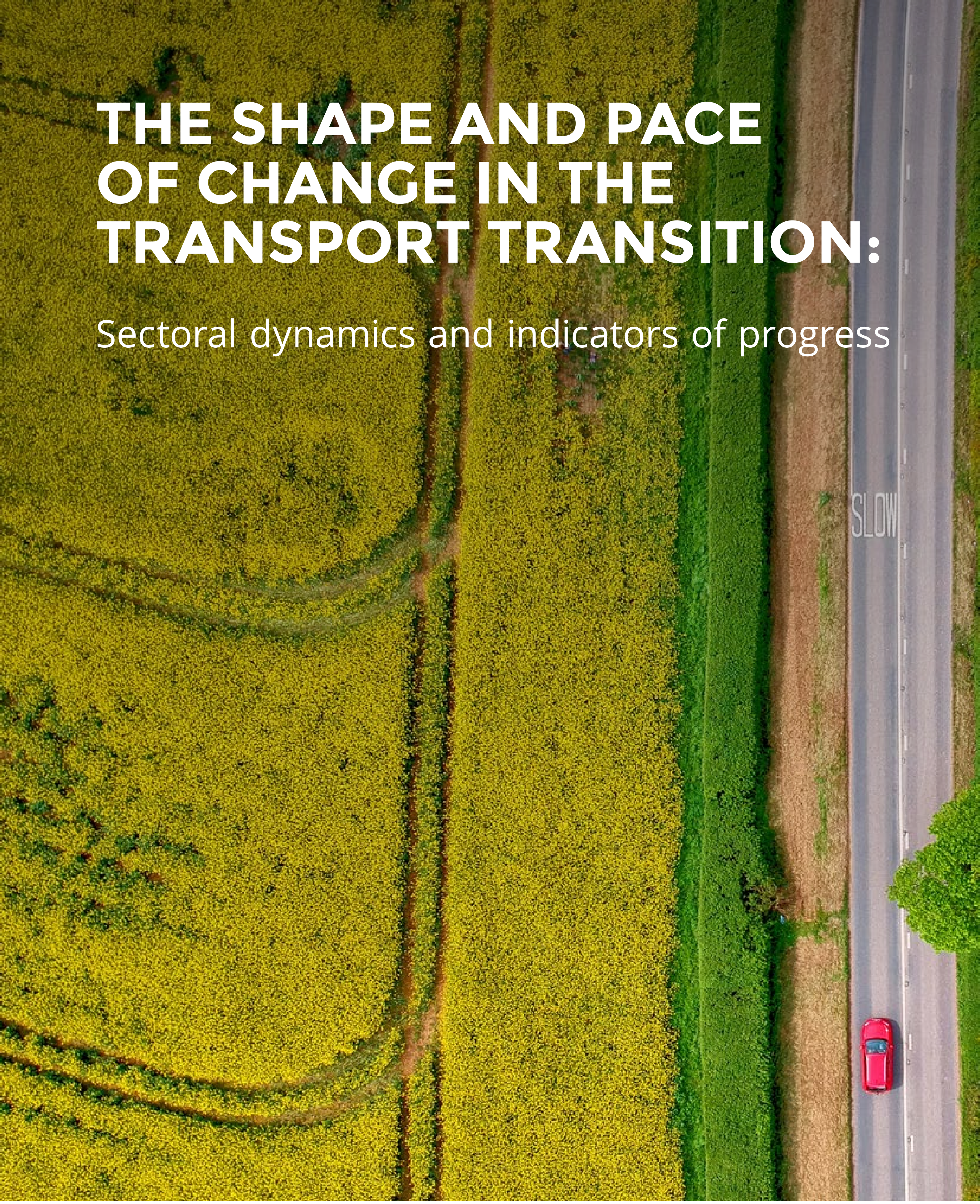
THE SHAPE AND PACE OF CHANGE IN THE TRANSPORT TRANSITION:

Sectoral dynamics and indicators of progress



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WE MEAN BUSINESS
COALITION

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LIST OF ACRONYMS

BEV	Battery Electric Vehicle
CAB	Climate Ambition Benchmarks
CAT	Climate Action Tracker
EV	Electric Vehicle
FCEV	Fuel Cell Electric Vehicle
HEV	Hybrid Electric Vehicle
ICE(V)	Internal combustion engine (vehicle)
LCV	Light-commercial vehicle
LDV	Light Duty Vehicle
NEV	New Energy Vehicle (NEV) Chinese program [covers Battery, Plug-in Hybrid and Fuel Cell vehicles]
PHEV	Plug-in Hybrid Electric Vehicle
TIAM	Times Integrated Assessment Model
ZEV	Zero Emission Vehicle

SUMMARY AND RECOMMENDATIONS

Change is not linear. Time and again, industry leaders, policy makers, and experts have been surprised by the pace at which new technologies transform markets and societies. From horses to cars, landlines to mobile phones, or videos to streaming. Technological innovation tends to follow the 'S-curve' (Figure ES-1): initially slow but incremental uptake (slight curve), followed by disruptive and radical diffusion (steeper curve) and finally culmination and stabilization (flattening curve).

Pursing efforts to limit global warming to well below 2°C and ideally 1.5°C, as set out in the Paris Agreement,[1] requires a steep decline in global greenhouse gas emissions towards zero by 2050. Rapid development and diffusion of zero-emission technologies are critical to reduce emissions at the pace and scale required.

Many assessments to date are based on current deployment levels and linear extrapolation, and are very pessimistic. Our assessment in this report uses the non-linear S-curve to examine rates of change to date, compared with those needed to achieve global climate goals, which underlines the risk of incumbents being caught out by disruptive technologies.

The power sector has to lead the global transition to a zero emissions economy. However, this transition also depends on other sectors that make use of energy switching from fossil fuels to renewable electricity. Transport is key. It accounts for 24% of energy-related CO_2 emissions, with passenger road vehicles – including cars, 2- and 3-wheelers, vans and buses – contributing to 45% of transport emissions. Like power, passenger vehicles also have an alternative technology that generates zero exhaust emissions and is ready to go – electric vehicles (EVs).

1 Namely: "Holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C." (UN, 2015). CO_2 emissions to reach net zero before 2050

S-CURVES REACHING FULL AND PARTIAL POTENTIAL

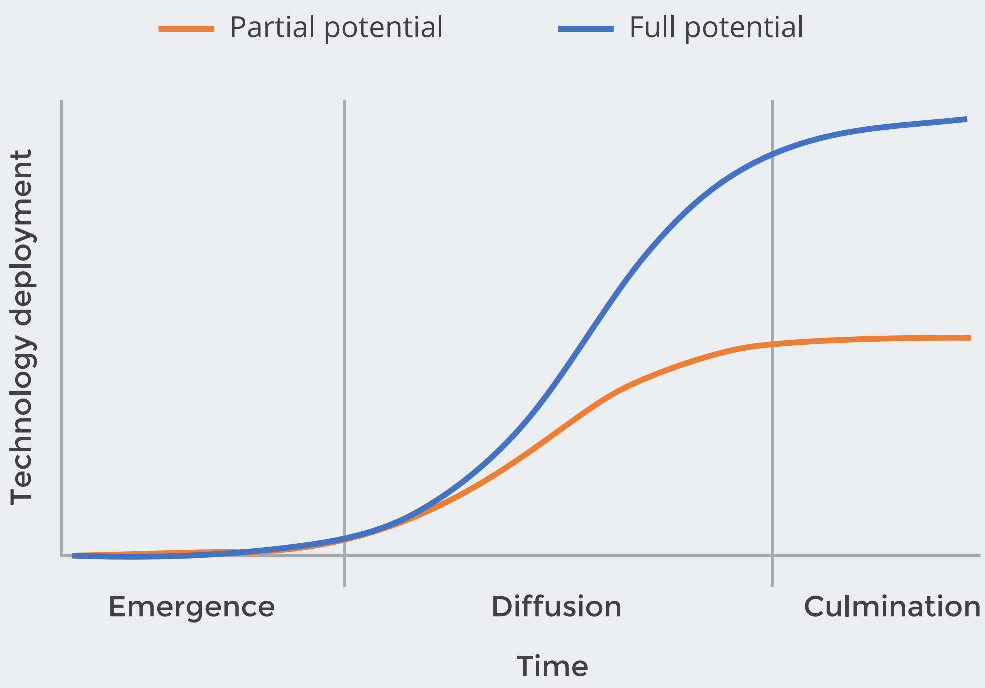

Figure ES.1: The S-curve

This is the second report on the dynamics of 'S-curves' relating to climate solutions and focuses on passenger cars (following a first report on renewable power). Electrification of road transport through EVs or zero emission vehicles (ZEVs)[2], in combination with a zero-carbon power system, is one of the most promising climate solutions available right now.[3] It complements the Climate Action Pathway for transport developed by the Marrakech Partnership for Global Climate Action and UNFCCC in support of the Paris Agreement implementation.[4]

We assessed current progress on uptake of EVs tracking against what climate science tells us is required to limit global temperature rise to well below 2°C and ideally 1.5°C, by looking at CO_2 trends and EV deployment, costs, and how to sustain and extend the transition. Now is the time to understand where we are on the switch to EVs and how to ensure growth happens at the pace required to achieve our climate goals.

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2 Electric vehicles include battery electric vehicles (BEV), hydrogen fuel cell electric vehicles (FCEV), and plug-in hybrid electric vehicles (PHEV). ZEVs are vehicles with zero tail-pipe emissions / zero emissions during use and only include BEV and FCEV. However, in this report EVs are largely synonymous with BEVs, except where otherwise specified.

3 Based on the scenarios from IPCC considered in this report, global transport sector CO_2 emissions need to fall by around 70% by 2050 from 2018 levels but this includes 'hard-to-abate' transport modes such as aviation, shipping and heavy haulage, for which low carbon technological solutions are more challenging. Low carbon options are relatively simpler and more available today for passenger transport, the focus of this study.

4 Climate Action Pathway 2020 – Transport: executive summary and action table. https://unfccc.int/climate-action/marrakech-partnership/reporting-and-tracking/climate_action_pathways

CO_2 EMISSIONS AND EV DEPLOYMENT

Transport CO_2 emissions are off track. Global transport emissions rose 18% from 2010 to 2018 and passenger road transport by 16% over the same period. Fuel efficiency improvements have helped and continue to be important. However, the increase in transport demand has cancelled out efficiency gains, and a technological shift is now essential to reach climate goals.

The growth of electric cars is heading in the right direction. The year-on-year increase in EV share of new car sales since 2015 has averaged around 41% per year. Contrasting a simple linear projection, if this exponential rate of growth were maintained, then EVs would account for all global new passenger car sales within two decades – by 2040 or shortly thereafter.

COSTS

Battery costs are falling rapidly. The cost of batteries, a major component of the cost of EVs, fell by 87% from 2010-2019. This has brought the purchase cost of electric vehicles much closer to that of petrol and diesel cars.

EVs are beating conventional vehicles on total cost of ownership. Even though capital costs of EVs remain higher than petrol and diesel cars, the running costs are lower, as the electricity required to charge the vehicle costs less than the equivalent quantity of fuel. This means that over the lifetime of the vehicles, EVs may already be less expensive to own and operate. During the 2020s, this trend is likely to continue for more and more vehicle classes around the world.

ELECTRIC CAR SHARE OF SALES 2005-2050

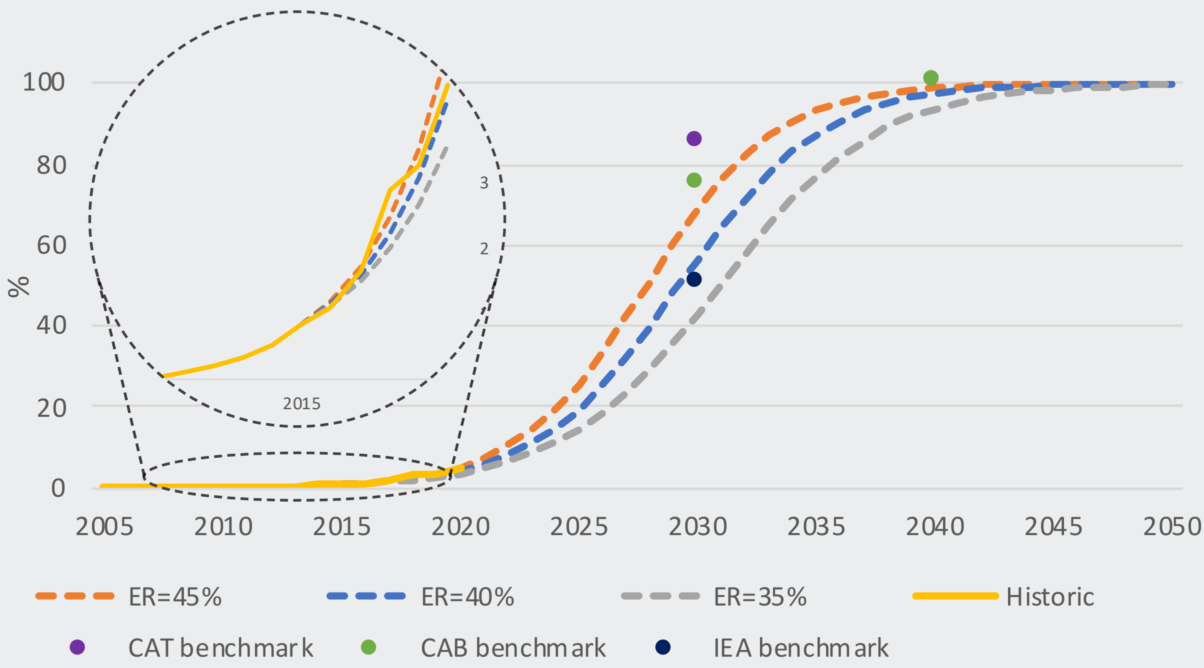


Figure ES-2: Electric car share of sales. Historic values from 2005-2020. Total sales of electric cars for 2005-2019 from IEA Global EV Outlook (IEA, 2020c), Statistical Annex, Electric Car New Registrations (BEV and PHEV) by country. Total sales of passenger cars for 2005-2019 from OICA (OICA, 2020a), Sales Statistics, New Passenger Car Registrations. 2020 electric car sales and total car sales calculated based on Irle (2021) and IEA (2020b). Share calculated from these data. S-curve projections start from 2015 values. Saturation point of S-curves set at 100%.

SUSTAINING AND EXTENDING THE TRANSITION

We find that a rapid transition is underway and appears to be unstoppable. However, its pace and depth will depend on policy and investments that focus on charging infrastructure and system integration, costs and investments, and supply and demand (Table ES-1).

- Policies must also support a 'just transition': a transition towards a climate-neutral economy that is implemented in a fair way, leaving no one behind.

Charging infrastructure and system integration. The global availability of publicly accessible charging equipment has grown 82% per year on average between 2010 and 2019. Policy recommendations are:

- Coordinate to ensure even coverage of public charging points and interoperability among different public and private charging points.
- Continue infrastructure expansion hand-in-hand with the integration across the full system: vehicle manufacturing, charging infrastructure, and power systems.
- Reward charging at off-peak periods and allow EV batteries to absorb surplus power from the grid, which will become increasingly important as the number of EVs increases.

Costs and investments in EVs. Many governments are already introducing policies that help overcome the high purchase costs of EVs and further reduce operation costs, usually in the form of subsidies or tax exemptions. In addition to this, governments can:

- Facilitate a leasing system and second-hand market for EVs and its batteries. This will require more attention as the market matures.
- Create alternative ways to generate revenue for infrastructure expansion and maintenance, for example, through taxation based on kilometers travelled.

Supply and demand. Governments are introducing a range of policies to accelerate the uptake of EVs in various ways: national and sectoral emissions reduction targets, ZEV/EV manufacturing mandates or sales targets, combined with restrictions on internal combustion engine vehicle sales and continued tightening of emission and fuel economy standards. Within specific countries these targets are Paris-consistent, but not at the global level. Policy clarity will attract financiers to invest and convince users to buy EVs. Building on experience from other countries, governments can go further by:

- Supporting domestic manufacturing and EV-related supply chains and battery recycling, thereby creating local jobs and facilitating the transition from existing ICE vehicle manufacturing.
- Committing to public procurement of EVs and programs to encourage private companies to commit to purchasing or leasing EVs – such as through the EV100 program. This will increase demand and build the confidence of vehicle and engine manufacturers to accelerate EV manufacturing.

BEYOND PASSENGER EVS

Finally, it is emphasized that passenger EVs are only one piece of the puzzle. With a rapidly shrinking carbon budget to remain within the 1.5°C scenario, we have to consider all available options, including those that are not considered zero-emission solutions in their own right. Governments can:

- Expand ZEV/EV policies to also cover light duty commercial vehicles and buses, and support technology development and uptake for medium- and heavy-duty trucks.
- Continue to focus on policies and programs that improve energy efficiency and use low emission fuels for all transport modes today, which will reduce the erosion of the remaining carbon budget.
- Enact policies that stimulate a shift away from private cars to public transportation, cycling and walking, as well as sharing vehicles and working from home to avoid the need for transport altogether.

Governments cannot achieve this on their own. Engagement of and collaboration with the private sector, research institutes, civil society and the wider public is an essential part to accelerate the S-curve transition.

Table ES.1: Summary of indicators and trends

System element	Indicator	Current status / recent trend	Benchmark	Paris-consistent*
CO_2 EMISSIONS AND EV DEPLOYMENT				
All transport	Total CO_2 emissions	+18% (2010-2018)	2.5 Gt/year (2050)	●
Passenger road transport	Total CO_2 emissions	+16% (2010-2018)	0.3 Gt/year (2050)	●
Passenger land-based transport - *vehicles*	CO_2 intensity per vehicle-kilometer	Declined below 200gCO_2/vkm, with new EU sales reaching 130gCO_2/vkm; seems to have slowed since 2010; some are further tightening standards to c. 100.	Trend in fleet averages need to accelerate to c. 100gCO_2/vkm by 2030;	●
Passenger land- transport - *people*	CO_2 intensity per passenger-kilometer	Current c.150 (LDVs) / 100 (all passenger transport) gCO_2/pkm and improvement slowing, below -1%/yr (2010-2015)	Would need to substantially accelerate instead towards 50 gCO_2/pkm (by 2030) and 0-10 (by 2050).	●
Passenger electric cars	Share of total passenger car stock	46% average annual growth (2015-2019)	>95% (by 2045-2055)	●
Passenger electric cars	Share of new car sales	41% average annual growth (2015-2019)	100% (2040: earlier for 1.5°C)	●
COSTS				
Electric vehicle	Purchase cost	Electric cars currently more expensive to purchase than comparable ICE options		●
	Total cost of ownership	Commonly cheaper than ICEs over the lifetime of the vehicle		●
	Battery pack prices	-87% (2010-2019)		●
SUSTAINING AND EXTENDING THE TRANSITION				
Charging infrastructure and system integration	Average annual growth of 82% per year, 2010-2019. Coordination may be needed to ensure even coverage and interoperability, as well as integrating vehicle manufacturing, charging infrastructure, and power systems			●
Costs and investments in EVs	Purchase and use subsidies, facilitate leasing and second-hand markets, alternative revenues for infrastructure expansion and maintenance. More attention needed to alternative financing mechanisms.			●
Supply and demand	Emission reduction targets, ZEV/EV manufacturing mandates or sales targets, ICE sales/access restrictions, emission and fuel economy standards. Support for domestic manufacturing and EV-related supply chains and battery recycling, public and private procurement of EVs.			●

**Green* indicates where indicators are plausibly consistent with keeping the global temperature increase to within the range of the Paris Agreement Aims, of 1.5°C to well below 2°C (see note 1), where possible with reference to benchmarks as illustrated in the text; red indicates trends that if sustained would put even 2°C out of reach. Achieving even a 50:50 chance of staying at or below 1.5°C itself would likely imply somewhat earlier goals for key benchmarks, such as requiring EVs to dominate global vehicle sales by 2030 and to extend rapidly at least to other land-based transport vehicles.*

SECTION 1: INTRODUCTION

1.1 AIMS AND CONTEXT

The Paris Agreement, signed in 2015 by 197 countries, declares the global community's response to the threat of climate change as "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UN, 2015).

Meeting this challenge requires major social and technological transformations to reduce greenhouse gas (GHG) emissions dramatically across all sectors of the economy. Emissions of the major GHG by volume, carbon dioxide (CO_2), would need to be net zero by around 2050.

How do the world's current social and economic systems, and the rate at which they are changing, measure up to this challenge? Is the world on track to meet the goals of the Paris Agreement? In this report, we consider these questions with respect to the transport sector. We look closely at the shape and pace of change, and the rates of growth and diffusion of key technologies, to examine whether the rate of change in this sector could be Paris-consistent, and some of the factors of influence.

1.2 THE TRANSPORT SECTOR

Transport currently accounts for 24% of global energy-related CO_2 emissions (IEA, 2020d). Passenger and freight road vehicles in combination account for nearly three quarters of transportation CO_2 emissions, and the vast majority of land-based transport emissions. Aviation and shipping account for 12% and 11% of total transport CO_2 emissions, respectively (Figure 1).

Transportation technologies have evolved around the availability of energy-dense liquid fossil fuels. Decarbonization of the transport sector is largely dependent on the development and deployment of alternative technologies based on zero-carbon energy vectors. Electricity is one of the most promising vectors for land transport. Electric vehicles (EVs) produce no emissions at the point of use.

The 'life cycle' emissions of electric transport include the assembly, disposal and recycling of vehicles and their component parts, and the means by which the electricity on which they run is produced. Figure 2 compares the lifecycle CO_2–equivalent emissions of internal combustion engine (ICE) vehicles and various alternative vehicle technologies. Crucially, the calculations assume the 2018 global grid average for CO_2 intensity of electricity, including transmission and distribution system losses, of 518 gCO_2-eq/kWh – somewhere between typical gas and coal power plants.

GLOBAL TRANSPORT CO_2 EMISSIONS, 2018
TOTAL: 8 GT CO_2 (BILLION TONNES OF CO_2)

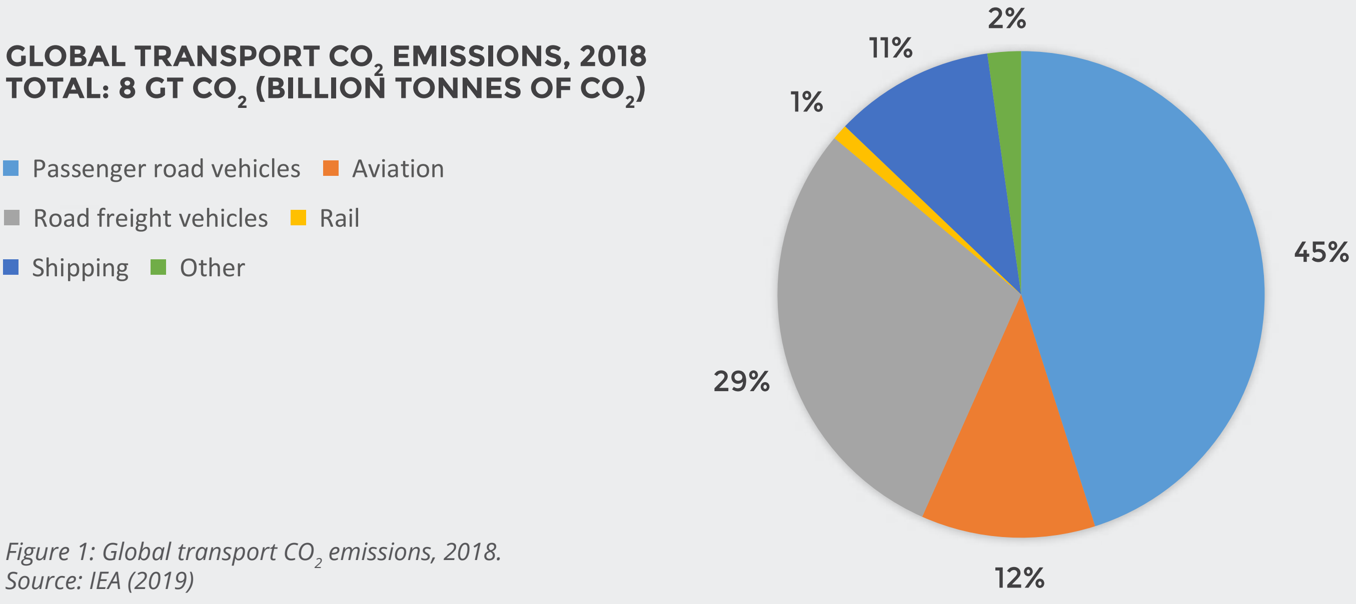


Figure 1: Global transport CO_2 emissions, 2018.
Source: IEA (2019)

Emissions resulting from manufacturing of the majority of the vehicle components do not differ substantially between EVs and ICEs. However, the manufacturing of EVs generates more emissions than ICE vehicles because EVs have much larger batteries. The 'well-to-tank' emissions from the generation of the electricity for EVs are substantially higher than for fuel production for ICEs, assuming the 2018 global grid average carbon intensity. However, this is more than offset by the lack of emissions from the direct use of EVs. Over the whole life cycle, EVs typically have lower emissions than conventional ICEs, despite some cases where the advantage could be marginal and the assumption of the 2018 carbon intensity of global grid average.

If low or zero-carbon electricity is used to charge EVs of course, the life-cycle emissions are much lower still, making the advantages of EVs over ICEs decisive. Decarbonization of the power sector is required for transport electrification overall to approach net-zero emissions.

Our previous report, The Shape and Pace of Change in the Electricity Transition, demonstrates this is already happening. As identified in the landmark study by David Victor et al. 2019, the electric vehicle transition is the emerging next transition – supported by the electricity sector trends and their implications for (rapidly declining) electric vehicles' Total Emissions of Ownership (TEO) as outlined in section 3.

Table 1 compares key metrics of the current global transport system – CO_2 emissions intensity (average emissions per unit of transport energy consumed or distance travelled); the share of the total energy demand from transportation modes that is supplied by electricity; and electric vehicle shares of new vehicle sales – with comparable benchmarks for a 2050 Paris-consistent transport system. The future benchmarks are derived from three sources. The first is Climate Ambition Benchmarks (Climate Works Foundation et al., 2019). The second is Climate Action Tracker of Paris Agreement Compatible Sectoral Benchmarks (New Climate Institute and Climate Analytics, 2020). The

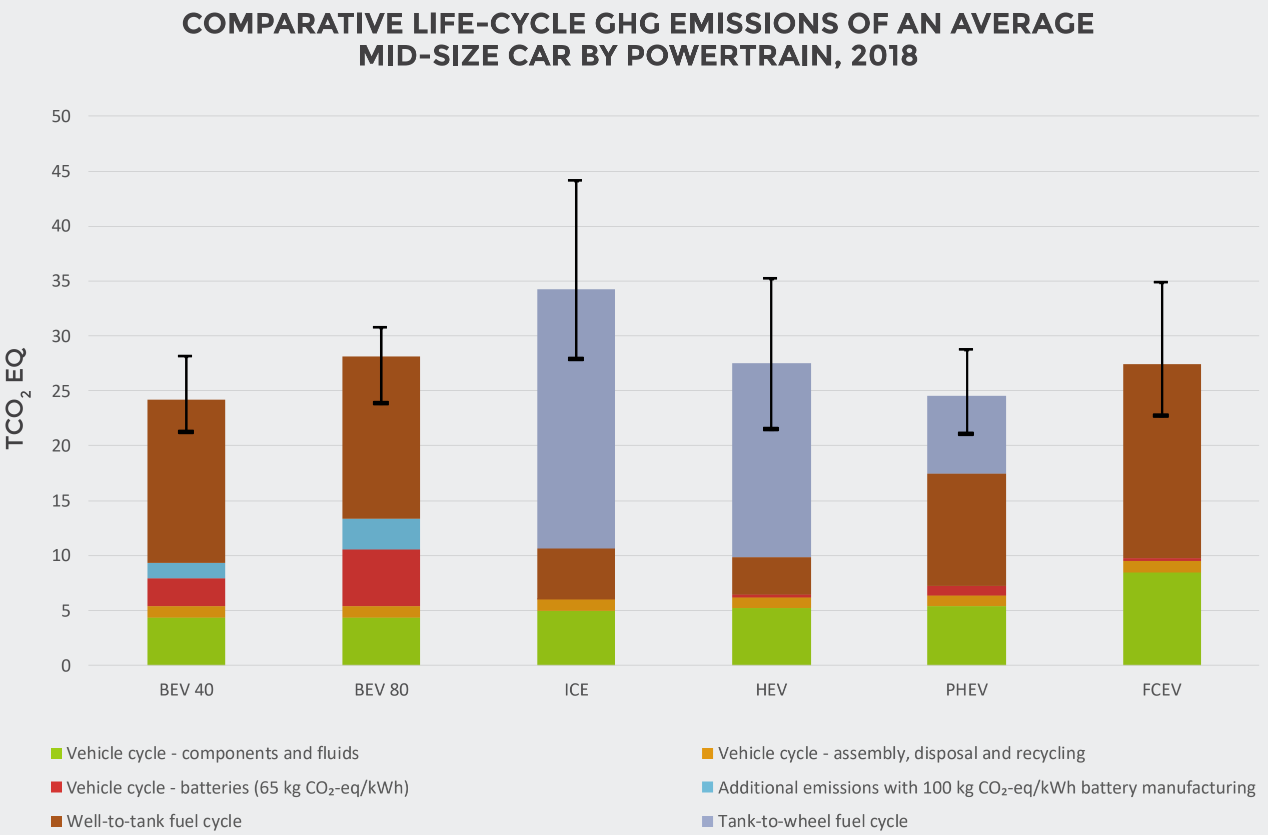


Figure 2: Comparative life-cycle GHG emissions of an average mid-size car by powertrain, 2018. Assumes GHG intensity of electricity generation of 518 gCO_2-eq/kWh, the 2018 global average including transmission and distribution system losses. Ranges show variation due to different vehicle size. BEV 40 = Battery Electric Vehicle with 40 kWh battery size. BEV 80 = Battery electric vehicle with 80 kWh battery size. ICE = internal combustion engine. HEV = hybrid electric vehicle. PHEV = plug-in hybrid electric vehicle with 10.5 kWh battery size. FCEV = fuel cell electric vehicle. Source: IEA (2020c) p. 191

third is a calculation of the median value of Paris-consistent scenarios from the database of scenarios that supported the IPCC's Special Report on Global Warming of 1.5°C (Huppmann et al., 2018), maintained by the International Institute for Applied Systems Analysis (IIASA). Further explanation of our process for selecting Paris-consistent scenarios from this database is given in the Technical Annex.

Table 1: Comparison of 2018 global transport system characteristics with selected benchmarks.

	2018 system (IEA, 2020a, IEA, 2020c, OICA, 2020a)	**Climate Ambition Benchmarks (CAB)**[5]	**Climate Action Tracker (CAT)**[6]	**Median of relevant Paris-consistent scenarios from Huppmann et al**[7]
CO_2 intensity	CO_2 intensity of road transport: **2018:** 68 gCO_2/MJ[8]		CO_2 intensity of land-based transport: **2030:** 35-60 gCO_2/pkm **2050:** 0-10 gCO_2/pkm	CO_2 intensity of total transport sector: **2030:** 61 gCO_2/MJ **2050:** 30 gCO_2/MJ
Share of electricity in transportation final energy demand	Share of electricity in transport final energy demand: **2018:** 1%[9]			Share of electricity in transport final energy demand **2030:** 5% **2050:** 23%
Electric vehicle share of new vehicle sales	EV share of new passenger car sales: **2018:** 3%[10]	EV share of new light duty vehicle sales: **2030:** 50-100% **2040:** >95%	EV share of new light duty vehicle sales: **2030:** 75-95% **2040:** 100%	

5 Climate Works Foundation et al. (2019)
6 New Climate Institute and Climate Analytics (2020)
7 Huppmann et al. (2018)
8 Indicator directly available from IEA data and statistics
9 Calculated from Total Final Consumption by Sector, and Electricity Final Consumption by Sector, both available from IEA data and statistics
10 Calculated from Electric Car New Registrations (BEV and PHEV) by country, IEA Global EV Outlook Statistical Annex; and New Passenger Car Registrations or Sales, OICA sales statistics

The table provides an overview of some of the key transformations required to achieve a Paris-consistent transport sector by 2050. The CO_2 intensity of land-based transport must be close to zero by 2050. For both the Climate Ambition Benchmarks (CAB) and the Climate Action Tracker (CAT), this requires electric vehicles to account for 100% of new light duty vehicle sales by around 2040. Solutions for decarbonizing aviation and shipping, and maybe heavy duty vehicles, are less clear. As a result, median values for 1.5°C-consistent scenarios from Huppmann et al. (2018)'s database show that when considering the entire transport sector, the carbon intensity does not reach zero by 2050, and the share of electricity in final energy demand is 23%. This reflects the existence of currently 'hard to decarbonize' modes within the transport sector, for which electrification is not currently considered the most viable option. The lack of options for decarbonizing such modes is one of the reasons why many 1.5°C-consistent scenarios require negative emissions to bring overall emissions back to 'net-zero'. The challenge is how to deal with these hard to decarbonize modes, either through negative emissions or through technological innovation that

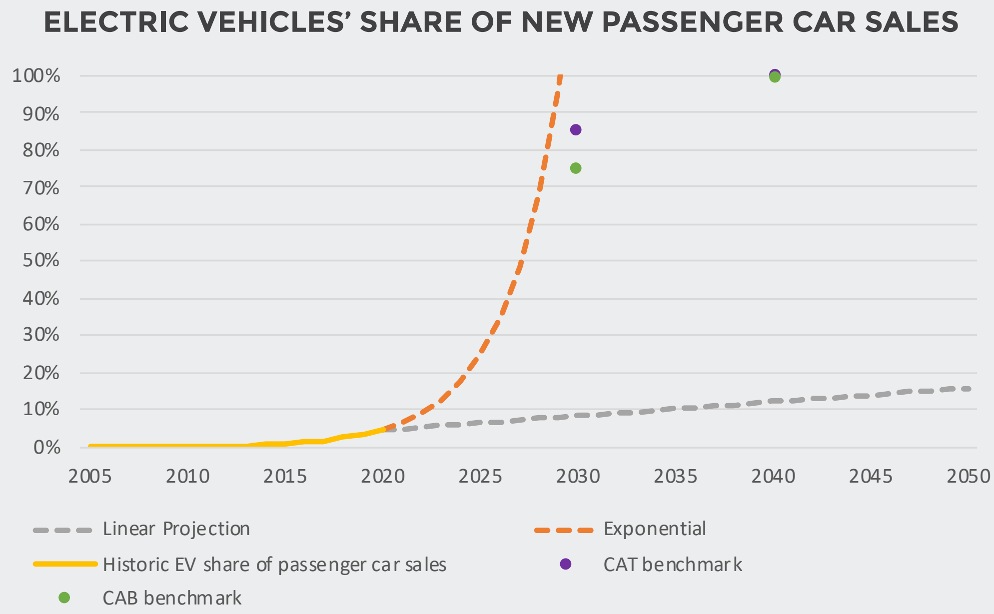


Figure 3: Comparison of linear extrapolation of historic trend in the EV share of new passenger car sales (2008-2020 average annual share increase), with exponential growth (41% annual year-on-year growth), and with 2030 and 2040 benchmarks derived from Climate Action Tracker (CAT) (New Climate Institute and Climate Analytics, 2020), and Climate Ambition Benchmarks (CAB) (Climate Works Foundation et al., 2019).

could bring electrification, hydrogen or advanced biofuels into aviation and shipping. This is of critical importance but beyond the scope of the current report.

We focus on passenger road transport – which as Figure 1 shows – is the largest single source of transport CO_2 emissions – and on electrification as the key technology to decarbonize this part of transport demand.

1.3 THE NATURE OF TRANSITIONS: CHANGE IS NOT LINEAR

Even focusing on the relatively known technologies associated with electrification of passenger road transport, the pace of change required is still substantial. A comparison of contemporary characteristics of global passenger road transport with Paris-consistent sector benchmarks for 2050 prompts the question: is the sector potentially on track to be Paris-consistent?

The relatively small share of electric vehicles in new passenger car sales today may easily give the impression that we are far from reaching 100% light duty vehicles sold to be electric by 2040 (Table 1). A straight-line projection based on current trends would confirm this impression. However, the dynamics of technological transitions are not so simple (see Box 1). Very often, the adoption of a new technology may be small before apparently rapid growth – an exponential, not linear, trend. The inverse is often true for the technologies which are displaced, so that they are removed from the system "gradually, then all at once," as in the case of coal power in the UK (Evans, 2020).

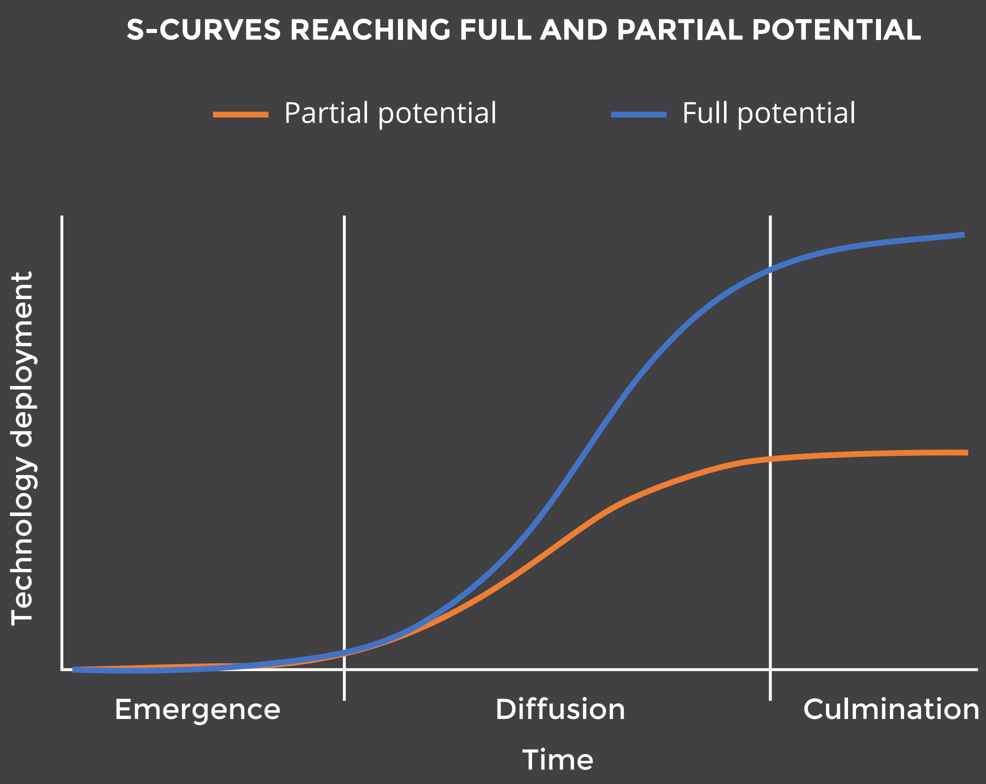
To illustrate this, Figure 3 also shows an exponential projection, in which the annual average year-on year increase in EV share of sales over the period 2015 to 2020 (41% per year) is maintained as a fixed annual rate of growth. This projection results in the benchmark of 100% share of EVs amongst new passenger car sales being reached as early as 2030. This is the old story of exponential growth, often acknowledged in theory but hugely underestimated in practice.[11]

11 As for example the old tale of wheat grains on a chessboard, and more prosaic examples noted in our electricity report Shape and Pace of Change in the Electricity Transition (note 6): and sadly more recently, in some regions, the explosion of Covid-19 cases when lockdowns were eased.

Box 1: Process and metrics of transition

Major transitions require new technologies and practices to emerge, improve, and displace incumbents. This tends to occur with an S-curve dynamic, characterized by an early ***emergent*** phase in which growth appears small, but growth then gathers magnitude as new technologies become established and enter a phase of widespread ***diffusion*** characterized by exponential rates of growth. This is followed by a final ***culmination*** phase when the pace of diffusion slows as the new technology stabilizes and its deployment begins to saturate (Figure 4). The level at which growth flattens may match the full potential of the technology, or may fall short of this if growth becomes constrained and begins to decline prematurely due to other factors. Historic examples of such S-curve dynamics include mobile communication technologies, jet engines, successive steel-making technologies, and the displacement of the horse and cart by motor vehicles.

Figure 4: The S-curve and its three phases



Many factors affect the rate of growth, and how long exponential growth can be sustained. Cost-competitiveness is an obvious but nonetheless important example. If a new technology is more expensive than the incumbent for the same type and quality of service, adoption beyond a small niche is unlikely. However, if it becomes cheaper, a stable rate of growth may persist for much longer, with the technology breaking through into new and larger markets.

Wider, systemic factors are also important. For example, some technologies exhibit "network effects" in which increased adoption generates benefits for the wider system. The attractiveness of such technologies may be limited while there are few adopters, resulting in slow growth; but as the number of users increases, their attractiveness is transformed and growth can be rapid. Network effects are often exhibited in telecommunications systems and technologies (Doganoglu and Grzybowski, 2007). In other cases the full functionality of a technology may depend on the existence of underlying infrastructures – physical, social and institutional. One example is automated teller machines (ATMs), the adoption of which took off rapidly once supporting IT systems and infrastructure were constructed (Watson et al., 2019). Another example is motor vehicles, which benefited from the construction of paved roads throughout the twentieth century (Nakicenovic, 1986).

Exponential growth cannot continue indefinitely. The ultimate limit is market saturation, when all potential demands for a technology have been satisfied. But well before this, numerous factors often lead to the rate of growth progressively declining, tailing off as saturation begins to appear on the horizon. For EVs, potential constraining factors are the availability of recharging infrastructure, problems with power system integration, or technological developments needed for expansion into more challenging market segments, such as vehicles capable of long distances, or heavy loads.

If technological transitions typically follow an S-curve dynamic, what are the implications for assessing progress in transport sector decarbonization, and future prospects?

First, it means that understanding the likely shape and pace of change between the current position and future benchmarks, is crucial to any evaluation of progress. Using simple straight-line extrapolation from recent trends to assess progress excludes consideration of these dynamics, and could result in a misleading and undue pessimism.

Second, it draws attention to the factors that may accelerate the adoption of decarbonizing technologies such that exponential growth rates are maintained for as long as possible, alongside factors that could cause these rates to decline prematurely: what progress is in turn being made with these elements, and how possible constraints may be eased.

1.4 OUR APPROACH

In this report, we use S-curve dynamics as a framework for assessing whether the transport sector is on track to be Paris-consistent by 2050.

Section 2 examines recent transport sector trends in CO_2 emissions and the deployment of electric vehicles. Based on the assumption that such trends represent the early stages of an S-curve transition it was determined whether or not the sector is on track to be Paris-consistent by 2050, with reference to key benchmarks (see Box 2). The key driving and constraining factors were identified that could affect the continuation of an S-curve-shaped trajectory by accelerating, sustaining, or decelerating technology adoption.

Section 3 examines the costs of batteries and electric vehicles as crucial factors for accelerating deployment through the diffusion phase. Section 4 focuses on wider systemic and policy-related factors which, if not addressed, might prematurely constrain growth and result in diffusion levelling out some way below its potential. Section 5 draws conclusions.

Box 2: Benchmarks as reference points for low carbon transport trajectories

Benchmarks provide a reference point against which to judge progress on various metrics. Five principal sources were used to identify benchmarks against which S-curve projections are compared (three of which were referred to in Table 1):

- Climate Action Tracker (CAT) report: benchmarks for overall decarbonization, including those which correspond to our transport-focused categories (New Climate Institute and Climate Analytics, 2020).
- Climate Ambition Benchmarks (CAB): a transport relevant benchmark on EV shares of new light duty vehicle sales (Climate Works Foundation et al., 2019).
- IPCC's database of scenarios that underpinned their special report on global warming of 1.5°C (Huppmann et al., 2018): median values from a set of relevant 1.5°C-compatible scenarios in order to identify benchmarks for 2030 and 2050 (see Technical Annex). In our recent report on the Shape and Pace of Change in the Electricity Transition, we used this database as our primary source for deriving 2030 and 2050 benchmarks. However, this database could not be used as our primary source for benchmarks in the current report, as it does not provide sufficient sub-sectoral and modal detail within the transport sector.
- UCL Times Integrated Assessment Model (TIAM): central 1.5°C scenario.
- Finally, the EV share of sales indicator is supplemented by a 2030 benchmark based on the Net-Zero Emissions by 2050 (NZE2050) scenario from the IEA's World Energy Outlook (2020e).

SECTION 2: TRANSPORT TECHNOLOGY DEPLOYMENT AND CO_2 EMISSIONS

This section considers the physical dimensions of the transport sector – its technology trends and CO_2 emissions. We compare recent trends with the early stages of illustrative S-curve trajectories that reach Paris-consistent benchmarks in 2050, and assess whether, and under what conditions, these indicators may be considered on track.

The benchmarks are based on five principal sources, as described in Box 2. After setting out broad indicators for the whole transport sector, the focus lies primarily on passenger road transport as this is the largest single-mode source of transport CO_2 emissions (Figure 1), and on electric vehicles as the nearest-to-market technology within this mode.

For each indicator we present recent historic trends, and plot S-curves starting from 2010 or 2015 and aiming to culminate at the 2050 or 2040 benchmark levels, so that recent trends may be compared with these projections.

The shapes of the S-curves are defined by three parameters:

- the **starting point** – defined by historic value in 2015 for the emergence phase of electric vehicles, with a view from 2010 for the wider transport trends;
- the **saturation point** – set at the level of the 2050 or 2040 benchmark; and
- the **emergence annual growth rate** – the maximum % annual growth rate as technologies begin to emerge, and which gradually reduces over time.[12]

12 The maximum annual growth rate is that experienced by a technology at the very first stages of growth, but which declines slowly over time to produce S-curve penetration. By the time a technology moves from emergence to diffusion, the annual growth rate will typically have reduced by only a small degree. For example, in Figure 6, annual growth in the S-curve with a 50% ER reduces from 49.9% in 2016 to 44.9% in 2026. In practice, for some years, annual growth rates may be much higher than this "maximum" rate. This highlights the fact that transitions are complex, with S-curves describing a general shape of transition rather than a narrow pathway from which there is no deviation.

2.1 SHARE OF ELECTRIC CARS: NEW SALES AND STOCK

Table 2: EV sales and in stock determined by selected benchmarks.

	Climate Action Tracker (CAT)	Climate Ambition Benchmarks (CAB)	IEA NZE2050 Scenario (WEO)
Share of EVs in new passenger car sales	**2030:** 75-95% **2040:** 100%	**2030:** 50-100% **2040:** >95%	**2030:** 50%
Share of EVs in stock	**2030:** 20-40% **2050:** 85-100%	**2045-2055:** >95%	

The share of electric vehicles in new car sales reached 3.3% by 2019 (4.5% in 2020). Since 2015, the share of EVs has grown at an average of 41% per year. S-curves projected forward on the emergence rate range of 35-45% closely approach the 2040 benchmarks, and exceed the IEA 2030 benchmarks though not the CAB and CAT 2030 benchmarks.

Given their recent emergence, electric vehicles accounted for only 0.6% of the total global stock of passenger cars in 2019 (0.8% in 2020). However, since 2015 this share increased at an annual average rate of 46% to 2019 (44% to 2020). Projected S-curves based on emergence rates of 40-50% succeed in meeting 2050 benchmarks, and the upper end of the range would also meet 2030 benchmarks.

This section focuses on passenger cars, and the shares of electric vehicles in sales and stock. Deployment of other passenger electric vehicle types are significant, including electric buses and two- and three-wheelers. However, the market dynamics for these vehicles are different to cars, and (especially for two- and three-wheelers) regionally differentiated (and data sources less consistent), so are discussed separately within Section 4.

By 2019, registrations of new electric vehicles exceeded 2 million worldwide, dominated by China (1 million), Europe (0.6 million) and the United States (0.3 million). Sales of electric passenger vehicles were also more resilient to the impacts of the Covid-19 economic downturn than for internal combustion engine (ICE) vehicles, reaching 4.5% of vehicle sales.[13]

Given their recent emergence, we focus on average growth rates since 2015 only, for calibrating the emergence rates of the S-curves (before this, the very low absolute numbers of vehicles meant that year-on-year growth rates were highly variable and less meaningful to use as a basis for extrapolation).

13 ITF (2020)

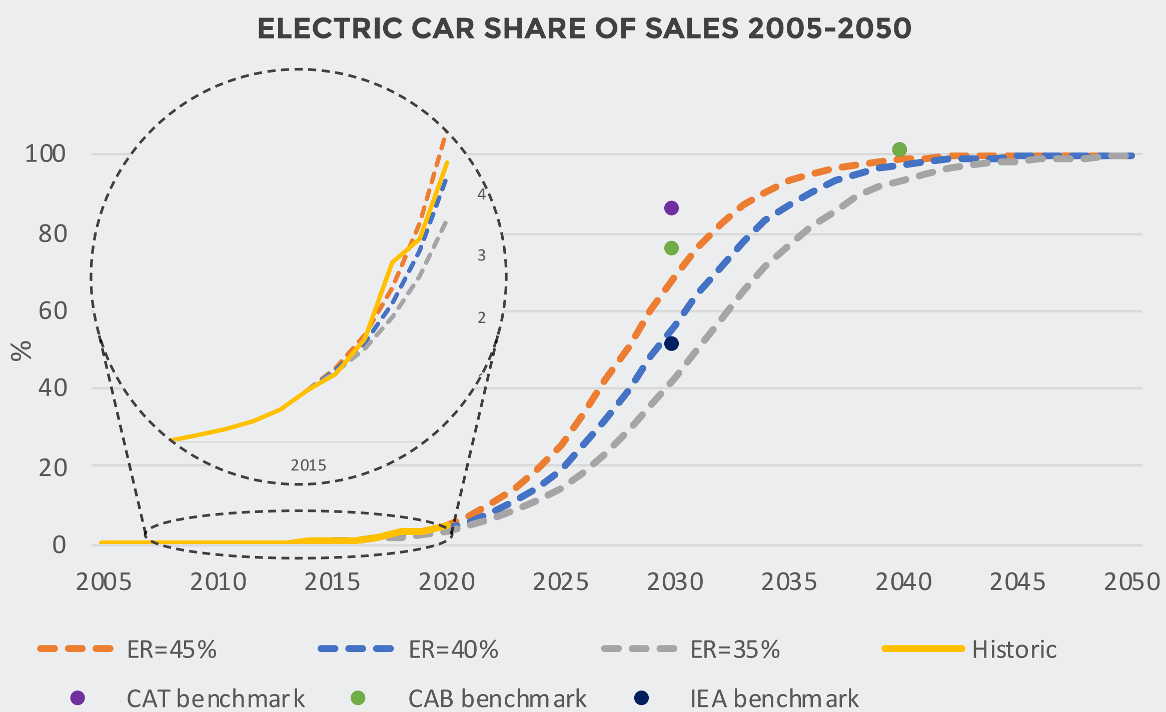


Figure 5: Electric car share of sales. Historic values from 2005-2020. Total sales of electric cars for 2005-2019 from IEA Global EV Outlook (IEA, 2020c), Statistical Annex, Electric Car New Registrations (BEV and PHEV) by country. Total sales of passenger cars for 2005-2019 from OICA (OICA, 2020a), Sales Statistics, New Passenger Car Registrations. 2020 electric car sales and total car sales calculated based on Irle (2021) and IEA (2020b). Share calculated from these data. S-curve projections start from 2015 values. CAT benchmark refers to LDVS, and 2030 value is the mid-point of the range. CAB benchmark is >95% in 2040, has been set here as 100%, and refers to LDVs. IEA benchmark refers to passenger cars and is based on the Net-Zero Emissions by 2050 (NZE2050) scenario from the World Energy Outlook (2020e). Saturation point of S-curves set at 100%.

Figure 5 compares the growing share of electric vehicles amongst overall car sales from 2005-2019 (callout-bubble), with S-curve trajectories starting from 2015. To reach close to 100% of EVs in electric car stock by 2050, EV sales would need to be approaching 100% at least a decade before that, allowing for turnover of the car fleet, so for this indicator we use 2040 benchmarks. Whilst still small in absolute terms, the observed annual average growth rate of 41% is consistent with S-curve shaped trajectories that achieve the Paris-consistent benchmark of close to 100% of new sales by 2040.

Figure 6 compares the electric car share of global passenger car stock from 2005-2019, with S-curve trajectories approaching the relevant Paris-consistent benchmark values in 2050. Since new sales are diluted in the pre-existing stock, the EV share of passenger car stock remains under 1%, but this share has been increasing at an annual average rate of 46% per year since 2015 - consistent with a range of S-curve shaped trajectories that meet the 2050 Paris-consistent benchmark.

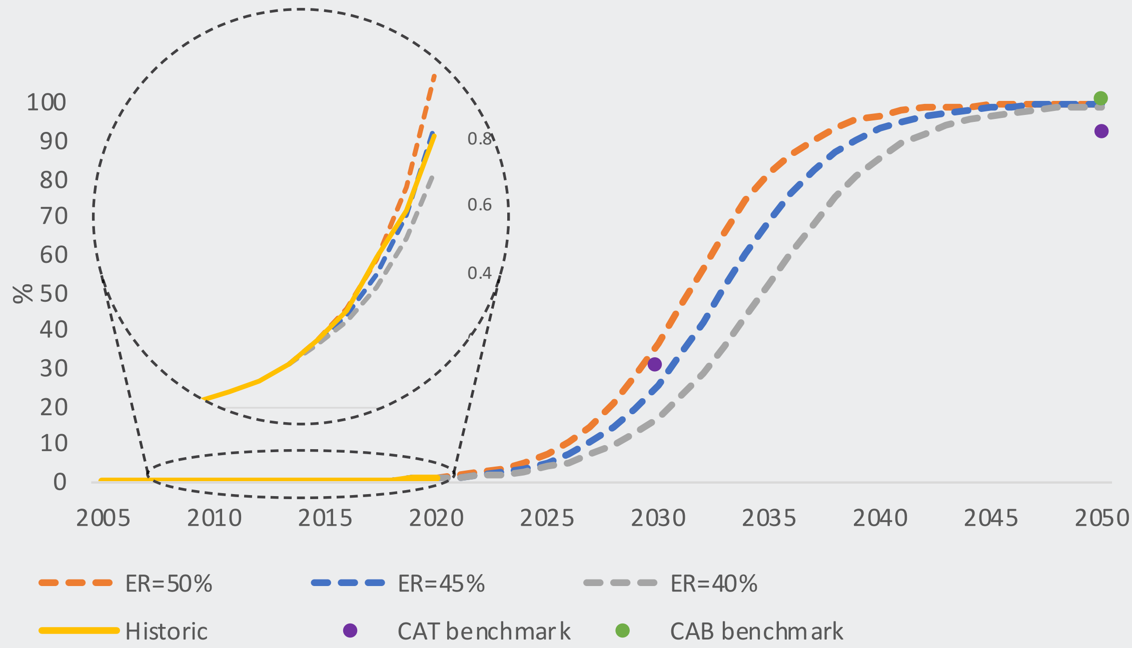


Figure 6: Electric car share of stock. Historic values for 2005-2020. Historic electric car stock for 2005-2019 from IEA Global EV Outlook (IEA, 2020c), Statistical Annex, Electric Car Stock (BEV and PHEV) by country. Historic total car stock for 2005-2015 from OICA, Passenger Cars, World Vehicles in Use (OICA, 2020b). 2016-2019 total car stock calculated by cumulatively adding annual new car registrations (OICA, 2020a) to the 2015 total. 2020 electric car stock and total car stock calculated based on Irle (2021) and IEA (2020b). Share calculated from these data. S-curve projections start from 2015 values. CAB benchmark is >95% in 2050, has been set here as 100%, refers to LDVs. CAT benchmarks are mid-points of ranges, and refer to LDVs. Saturation point of S-curves is set at 100%.

2.2 PASSENGER ROAD TRANSPORT: CO_2 INTENSITY AND EMISSIONS

Table 3: Emissions and emission intensity of passenger road transport determined by selected benchmarks.

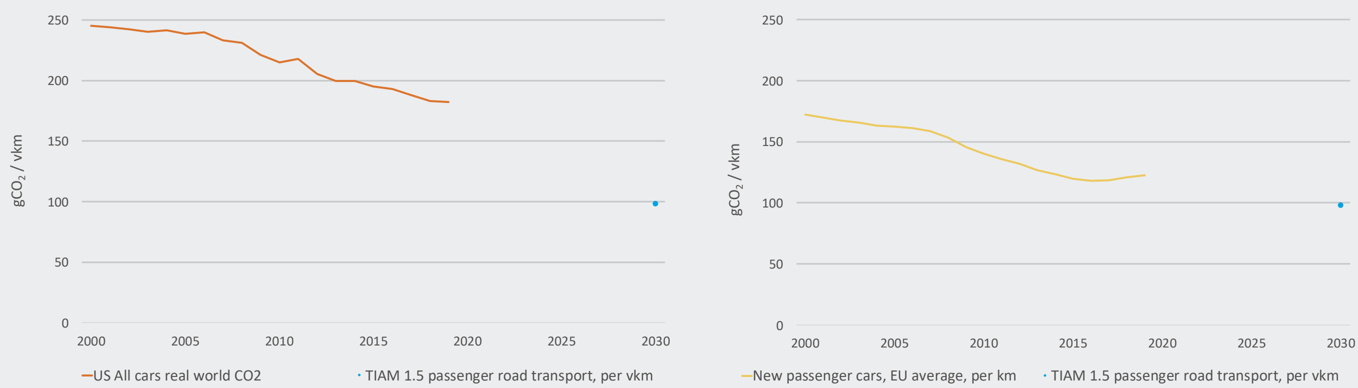
	Climate Action Tracker	Huppmann et al. /CAT	TIAM 1.5
CO_2 emissions	-	**2030:** 2.1 Gt/year **2050:** 0.3 Gt/year	**2030:** 1.46 Gt/year **2050:** 0.1 Gt/year
CO_2 intensity of energy service demand	**2030:** 35-60 gCO_2/pkm **2050:** 0-10 gCO_2/pkm		**2030:** 98 gCO_2/vkm **2050:** 4.0 gCO_2/vkm

The trend in CO_2 emissions from passenger road transport since 2010 is not Paris-consistent, but the trend in CO_2 intensity is moving in the right direction. However, steeper reductions over the coming decades cannot be delivered by further efficiency improvements in ICEs, but require major transitions to alternative technologies such as electric vehicles.

Passenger road transport is the largest single-mode source of transport CO_2 emissions, and the 'hard to decarbonize' sub-sectors within overall transport puts particular pressure on passenger road transport as the priority – and potential launch-pad - to decarbonize transport.

Both the vehicle efficiency and uses (such as occupancy) of cars vary considerably between regions. Figure 7 shows trends in CO_2 emissions per vehicle kilometer to 2019, for the US and EU, respectively for on-road average and new sales. The historic decline in average grams-CO_2 per vehicle-kilometer reflects improved vehicle efficiency, particularly as vehicle standards took effect from the mid (EU) and late (US) 2000s.[14] On-road CO_2-intensity has been improving in the US as these more efficient vehicles work through

14 In the EU the fleet-wide target for average emissions of new passenger cars was 130gCO_2 / km between 2015-2019. This target was surpassed 2 years early in 2013, and then continued to fall until 2016 (EC, 2020b). However, after this point the emissions intensity of new vehicles began to rise slightly, and in 2019 it stood at 122 gCO_2 / km (Figure 23), prior to new and much tougher standards coming in from 2021 (see section 4). The US has regulated the fuel efficiency of vehicles manufactured since the 1970s at a federal level, under the Corporate Average Fuel Economy (CAFE) standards. The Safer Affordable Fuel-Efficient (SAFE) Vehicles rule sets fuel economy and CO_2 standards with increased stringency, but with ongoing dispute about the rate of improvement, and whether States have the right to continue to apply the more stringent regulations in contrast to the federal position (IEA, 2020c), reflecting the unstable partisan politics around energy and environment in the US.



(a) Average CO_2 intensity per vehicle km – all cars on-road average, US data

(b) Average CO_2 intensity per vehicle km – fleet average new passenger car sales, EU

Figure 7: CO_2 intensity in grams CO_2 per vehicle kilometer of cars in the US and the EU, 2000-2019. Panel (a) shows data for US all cars, real world, fleet-wide average, from EPA (2019). Panel (b) shows data for new passenger cars in the EU. Both datasets are compared to the global average 2030 benchmark for all passenger road transport, gCO_2 / vkm, from the TIAM 1.5 central scenario.

the fleet, but from substantially higher levels; in the EU, efficiency of new sales stopped improving after the 130g/CO_2 standards were met, though much tougher standards take force in 2021. Future standards are discussed in section 4. Sustaining such reduction will require going far beyond incremental improvements in ICE technologies as discussed there.

Most directly relevant for global CO_2 are trends in CO_2 intensity relative to passenger-distance travelled (i.e. the 'service demand'), for which global data are available and shown in Figure 8. This shows CO_2 emissions per passenger-kilometer (pkm) travelled, for different modes/combinations.[15] The emissions intensity of passenger light duty vehicles (LDVs) has fallen strongly since 2000 but remains by far the highest. The average emissions intensity of all

15 ICCT data for: all passenger land-based transport (including rail); all passenger road transport; and passenger light duty vehicles (LDVs) only.

passenger road transport – including two- and three-wheelers and buses – is much lower. This indicates in principle the potential contribution of modal shift – e.g. moving from a private car to a bus or train – as well as technological improvement within modes, for reducing emissions intensity. However, in contrast, the global average emissions intensity per pkm of passenger land-based transport appeared to slow since approximately 2010, falling by only 5% from 2010 to 2015 (subsequent data not found) – less than 1%/yr.

Benchmarks indicated on Figure 8 are mid-point ranges for this CAT indicator,[16] the scope of which is equivalent to all passenger land-based transport; we show a linear trajectory from the 2010 value, with a 2030 midpoint indicating almost a doubling of efficiency (halving of CO_2 intensity).

16 Based on 'emissions (in gCO_2) per pkm travelled by cars, two and three wheelers (only in the case of China, Indonesia and India), buses, and rail transport' (New Climate Institute & Climate Analytics, 2020). The benchmarks given here are the mid-point of ranges for this CATindicator.

CO_2 INTENSITY PER PASSENGER KILOMETRE

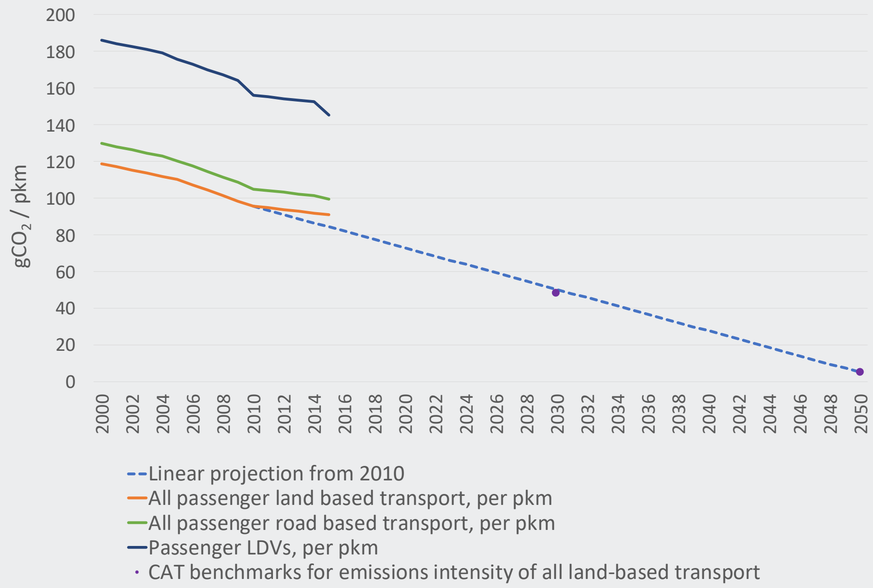


Figure 8: Historic and projected (2010-2050) CO_2 intensity of global passenger land-based transport (eg. including rail), passenger road based transport, and passenger light duty vehicles (LDVs), per passenger kilometer. Historic data from ICCT (2017). CAT benchmarks are for emissions intensity of all land-based transport in gCO_2 / passenger kilometer, and are the mid-points of ranges. The linear projection starts from the 2010 value for all passenger land-based transport, being the indicator of closest equivalence to the CAT benchmark.

The apparent slowdown in vehicle intensity improvements since 2010 may be due to a combination of several factors. In practice, global modal shifts have likely been away from more CO_2 efficient modes (e.g. public transport, 2- and 3-wheelers) in developing countries, towards passenger cars - with a CO_2 impact exacerbated by the tendency for less efficient models to be exported to developing countries when they have been ruled out by tightening standards in EU and US. Developed countries have also seen a trend within private cars towards heavier vehicles (e.g. SUVs). Finally, incremental improvements to existing technologies and practices are reaching a limit. The fact that the linear trend has not been maintained is the surest indicator that incremental change is not enough – and that new technologies - and potentially, new land transport infrastructures, modes, technologies and choices – need to grow rapidly and start to dominate. Incremental improvements in the emissions intensity of conventional ICE vehicles do potentially help to buy time within the constraints of overall carbon budgets, along with support for modal shifts. However, this does not (and must not) preclude the more fundamental shift in transport technologies, but rather support it. A smarter, and more integrated transport system is perfectly compatible with electric and other ZEV drivetrain technologies. More efficient transport provision may also facilitate electrification, as it could help to reduce pressure on the electricity supply system, and on critical minerals required for EV batteries.

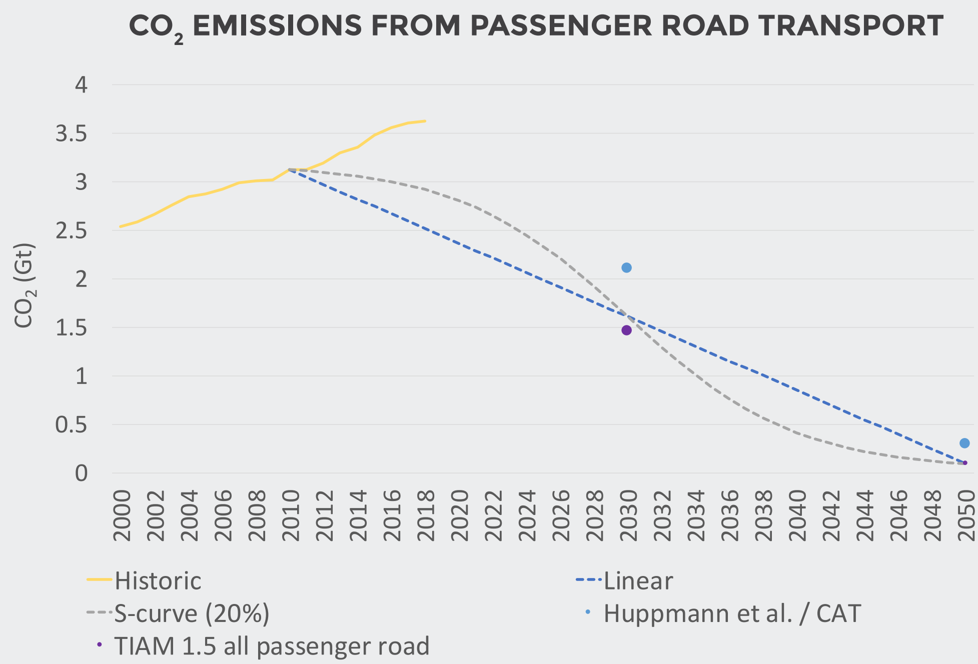


Figure 9: Historic (2000-2018) and projected (2010-2050) CO_2 emissions from passenger road transport. Historic emissions data from IEA (2019) 'passenger road vehicles'. Huppmann et al. / CAT benchmarks calculated by multiplying the CAT emissions intensity benchmarks (gCO_2 / pkm) by the median values for 2030 and 2050 of passenger road energy service demand (pkm) from relevant scenarios in Huppmann et al (2018). TIAM 1.5 benchmarks are values for all passenger road transport in the TIAM 1.5 central scenario. End point for linear and S-curve trajectories set by TIAM 1.5 values.

The overall scale and urgency of the transition is underlined by Figure 9, which shows overall global CO_2 emissions from passenger road transport still steeply rising, being 16% higher in 2018 compared to 2010 levels. The figure also includes a 'what if' historical S-curve: what if zero-carbon transport modes had started to displace all passenger road transport since 2010 with an emergence growth rate of 20% per year. That would have just about achieved the benchmarks. The delay, combined with globally rising demand, means that far faster rates of emergence are now required – seeking to almost halve global passenger transport CO_2 by 2030.

This growth in CO_2 emissions from passenger road transport has been largely caused by growing demand. This is clear when contrasting this trend to the CO_2 intensity of passenger road transport (Figures 7 and 8), exacerbated by the fact that road transport has remained dependent on refined fuels, with CO_2-energy-intensity (grams of CO_2 per megajoule (MJ) of energy used) barely changed, combined with the slowing trend of efficiency improvements.

Broadly, these figures illustrate two issues. First, although there has been some progress in improving the emissions-intensity of vehicles (by either metric), any effect of this on absolute emissions has been more than cancelled out by the increase in transport demand. Future increases in transport demand and in the size of vehicles, coupled with transfer of second-hand and less efficient vehicle lines to developing countries, will pose a major challenge to reducing road transport emissions over the coming decades. Second, despite significant improvements in ICE efficiency, the benchmarks cannot be achieved with engine technologies that consume fossil fuels, hence, as well as near-term incremental improvements, an increasingly urgent and rapid technological shift is required.

All this underlines the central need for the combination of changes in transport demand patterns with fundamentally new transport technologies. Fortunately, as we have seen, EV sales since 2015 have been growing at over 40%/yr. Whether or not this can bring us close to the benchmarks for Paris-consistent transport globally will depend not only on whether such growth can be sustained, but also what happens more widely to transport demand.

2.3 TOTAL TRANSPORT CO_2 EMISSIONS

Table 4: Emissions from passenger road transport determined by selected benchmarks.

	Huppmann et al.
CO_2 emissions	**2030:** 5.7 Gt/year **2050:** 2.5 Gt/year

The trend in CO_2 emissions from all transport together is incompatible with any climate goals (and would put further pressure on oil reserves,

markets and price stability). The direction of the trend must be reversed rapidly, through a combination of technological change, modal shift and demand side reduction.

Figure 10 shows that total transport CO_2 emissions – which closely mirror the sector's oil consumption - have been rising steeply. The trend in passenger road transport observed above is mirrored and accompanied by equivalent increases in freight, marine and aviation. The global CO_2 emissions from transport overall, over 8 $GtCO_2$, are more than twice that of passenger road transport alone, and amount to over 20% of total global CO_2 emissions.[17]

In this case, the 2050 Paris-consistent benchmark based on Huppmann et al. does not reach zero – this reflects the assumed persistence of emissions from some of these 'hard-to-decarbonize' sectors within transport. Remaining emissions within Paris-consistent scenarios typically imply that negative emissions are required elsewhere in the system, to offset the most difficult remaining sectors.

This underlines the overall breadth and scale of the transport challenge. Transport now dominates oil demand. Transport is the major source of local air pollution. And, with electricity now on a decarbonizing trajectory, transport along with industry will soon be the biggest CO_2 emitting sectors.

The impact of COVID has underlined both challenges and opportunities. Travel curtailment – particularly of aviation – reduced emissions, through impacts that were largely unwelcome, but which also underlined the remarkable capacity of new communications technology. Many welcomed the cleaner and quieter cities, some of which have been spurred to newer, cleaner and greener city transport strategies and infrastructure design. The role of light commercial vehicles (LCVs) – which are another strong candidate for electrification given their high mileage and short distance ranges – surged with the increase in online shopping.[18]

The overall solutions will have to be broader than just electric vehicles. Yet, just as progress in wind and solar electricity is spearheading bigger changes in electricity, EVs are clearly in the vanguard of the transport transition. Transport overall is beyond the scope of this study – but the future pace of progress in EVs, and associated technologies like advanced batteries, is nevertheless likely to be the biggest determining factor for wider transport prospects. The rest of this report focuses on EVs' future prospects.

17 CO_2 emissions from fossil fuels and industry in 2018 / 2019 were close to 38 billion tonnes ($GtCO_2$/year). Land use emissions are estimated to add about 5 $GtCO_2$/year, but with bigger annual fluctuations and uncertainties on the land use flux.

18 ITF (2020)

CO_2 EMISSIONS FROM ALL TRANSPORT MODES

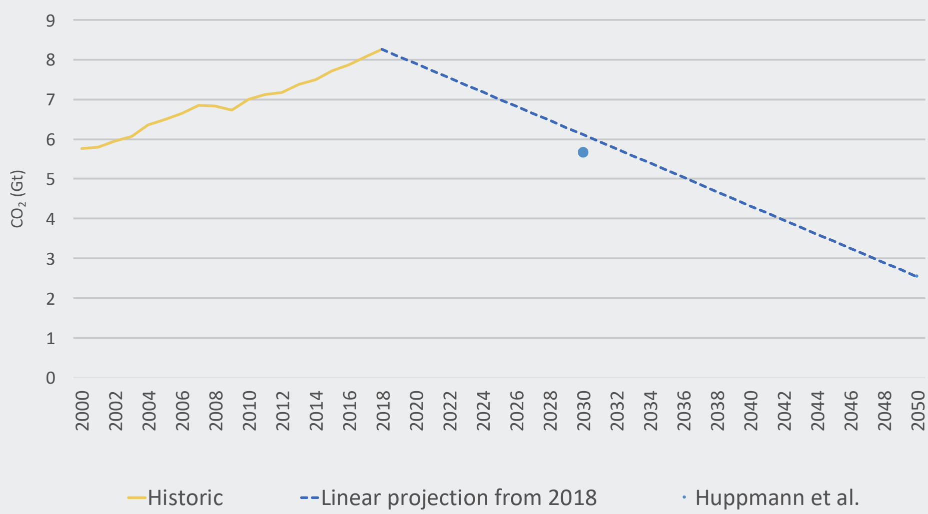


Figure 10: Historic (2000-2018) and projected (2018-2050) CO_2 emissions from transport. Historic emissions data from IEA (2020a). Benchmarks derived from Huppmann et al. (2018).

SECTION 3: COSTS, PRICES AND LIFE-CYCLE EMISSIONS

Despite adverse trends in transport sector CO_2 emissions, the pace of growth in the share of electric vehicles in both total stock and total sales of passenger cars is potentially on track for 2050 benchmarks, assuming an S-curve shaped transition. Can and will this be sustained?

Cost is an important factor affecting the dynamics of a technology transition, particularly the costs of delivering an existing energy service through new technology relative to the incumbent. In the transport sector a key comparison is between the costs of EVs and ICE vehicles of otherwise similar characteristics. This section considers first the overall costs, and then trends in a key system component of EVs, the battery.

3.1 TOTAL COST OF OWNERSHIP

EVs typically have higher upfront costs than ICE vehicles, but lower fuel and maintenance costs mean that over time the 'total cost of ownership' (TCO) of an EV is often lower. Over time, relative TCOs will increasingly favour electric cars over ICE vehicles as production costs decline and market share increases, and measures to tackle local air pollutant and CO_2 emissions continue to spread and become more stringent.

EVs at present tend to cost more to produce (and consequently to purchase, in the absence of subsidies) than their ICE vehicle counterparts in the same vehicle segment. The top-selling brand, Tesla, adopted a deliberately high-end strategy to focus on rich consumers and build a brand of high quality and performance. The Tesla Model 3 retails in the UK at around £46,000 (around USD 64,000) (EDF, 2020b). Figure 11 shows that this was still the highest seller in 2020 – with over 140,000 deliveries in the first half of the year - but had been joined by a wide range of others led by the Renault Zoe (almost 40,000 sales) and many others around 20,000 sales, most of which are aimed at a wider potential clientele: vehicles such as the Zoe, the Nissan Leaf and the VW e-Golf, are marketed at below £30,000 (around USD 42,000) (EDF, 2020a). Two

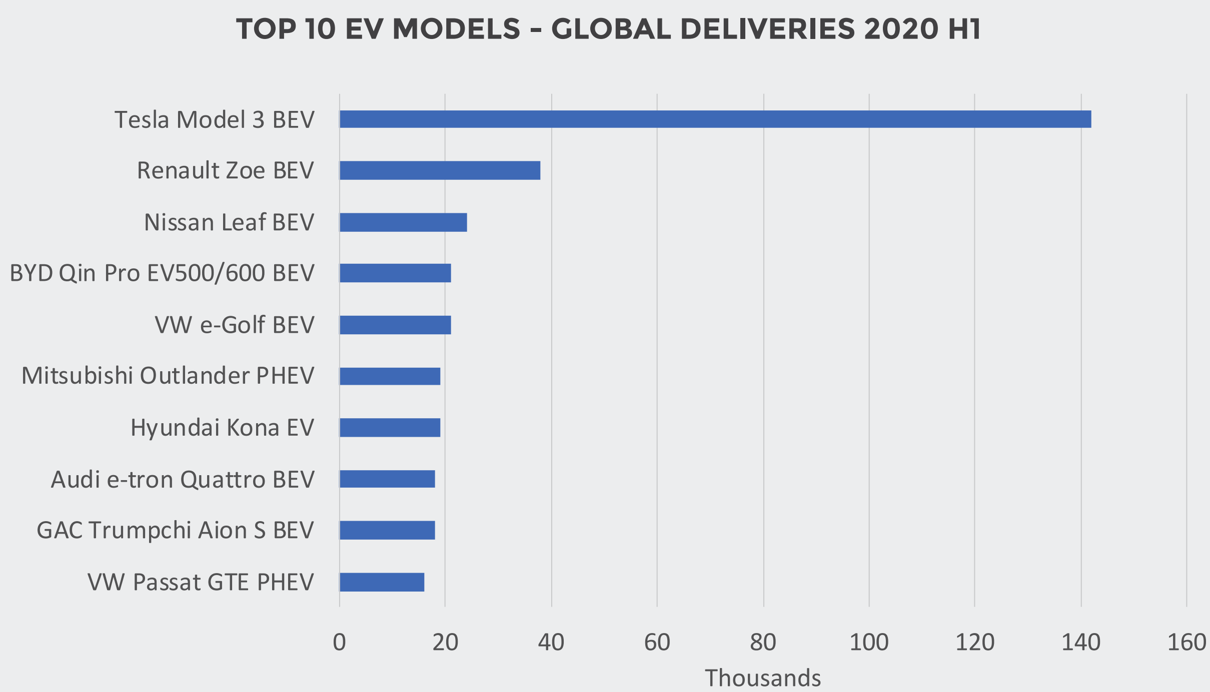


Figure 11: Top 10 EV models by deliveries from January to June 2020. Source: Irle (2020)

Chinese manufacturers in the top 10 – BYD and GAC – retail at the equivalent of USD 20,000 - 30,000 dollars in China – and reflect not only the significance of the Chinese market itself but their growing interest in global exports.

In general the purchase costs of EVs are at present still slightly higher than a typical family car. However, this is just one element of the total cost of owning and operating a vehicle. EVs are typically cheaper to run than ICE vehicles, and maintenance costs are usually also lower. Such trends are broadly true irrespective of geography and vehicle segment. However, to these factors must be added the costs imposed and benefits afforded by very different policy regimes around the world, before comparative TCO values can be calculated.[19]

Figure 12 presents an illustrative TCO comparison for EV and ICE versions of one of the top-five models, in the UK. Three variations for the TCO of the electric option are presented to illustrate the influence of two key components of the overall cost to consumers (the availability of subsidies and the rate of depreciation), discussed below.

19 Also, assumptions around financing costs matter – EU assessments of low carbon transition having being recently criticized for assuming implausibly high discount rates, far higher than commercially available, let alone available to governments, which discriminates against low carbon investments including in transport. As low carbon options – for both electricity and transport are more capital intensive but have lower operating costs, assumptions around interest rates can have a substantial impact on cost comparisons, including total cost for EVs in particular – see CISL (2021) for further discussion. For simplicity, we do not discount the values in Figure 12, beyond vehicle depreciation.

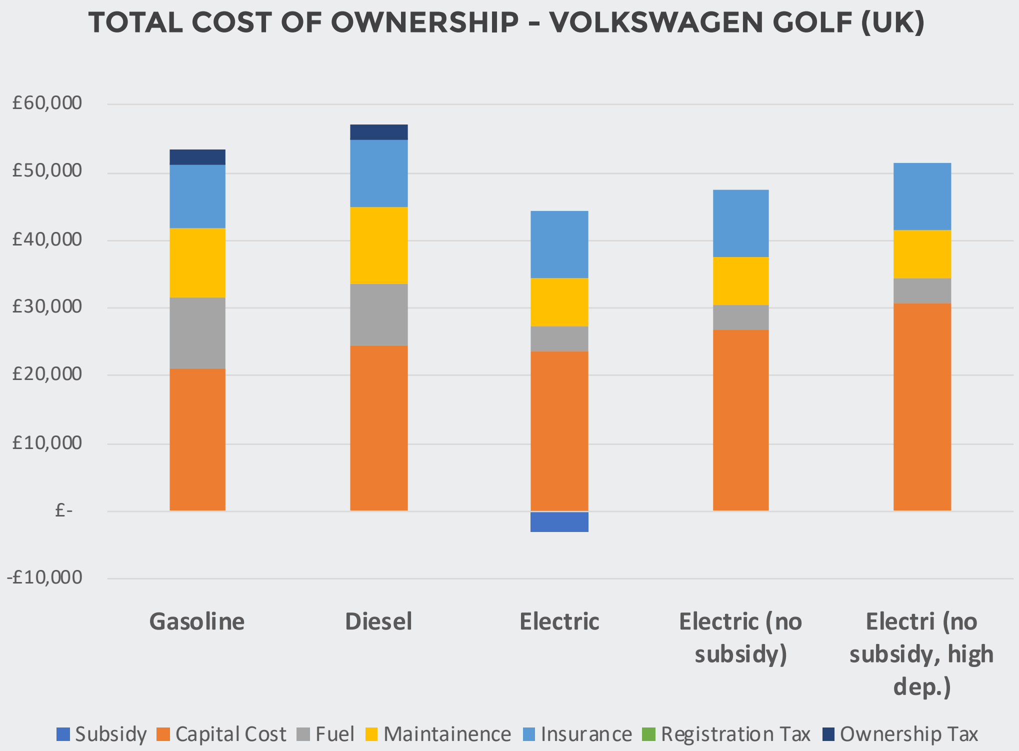


Figure 12: Total cost of ownership. Sources: De Clerck et al. (2016), Volkswagen (2020) and Welford (2019).[20]

20 Vehicles are Volkswagen Golf Life 8 5 Door 2020 edition, 1.0 TSI (gasoline) and 2.0 TDI (Diesel), and Volkswagen e-Golf. Capital costs are 'On the Road' (OTR) costs, excluding subsidies and registration tax (VED First Year Rate), and are £23,125, £24,725 and £31,075 respectively. Registration tax = £175 for gasoline/diesel, zero for electric. Electric purchase subsidy of £3,000. Depreciation rates = 84.5% for gasoline (De Clerck et al, 2016), 73% for diesel (Volkswagen, 2020) and 87% for electric (Welford, 2019). Ownership tax = £150/year for gasoline and diesel, zero for electric. Fuel consumption of 5.5l/100km and 4.65l/100km for petrol and diesel respectively, and 15.4kWh/100km for electric. Energy prices assumed as £1.14/l, £1.17/l, £0.14/kWh, respectively. Maintenance costs of 6.1p/km and 6.8p/km for gasoline and diesel respectively, based on 50,000 miles over 5 years, using the running cost calculator at Fleetnews.co.uk. Annual insurance prices of £673, £701 and £715 for gasoline, diesel and electric respectively, based on respective insurance bands and assuming owner is 40 years old. Calculations assume a single owner for a vehicle lifetime of 14 years, driving 12,000km per year. For simplicity, finance costs are excluded.

Based on values from November 2020 for three versions of the Volkswagen Golf (one of the best-selling models in the UK), the diesel drivetrain has the highest TCO, whilst the electric option including subsidy was the cheapest.

As might be expected, the capital cost is the single largest element of the TCO for all types of vehicle. Although the list price of the electric version is around 30% higher than the ICE options, diesel has the highest lifetime consumer cost. A capital subsidy of £3,000 (around USD 4,200) reduces the purchase price of the electric option to 14% and 21% above the diesel and gasoline options, respectively.[21]

Depreciation is the rate at which the value of the vehicle declines over time, determining the value at which it may be resold. EVs have tended to depreciate more quickly due to their (real or perceived) limitations relative to ICE vehicles. Increases in battery capacities in new EVs may also have served to reduce the re-sale value of the now relatively low-range early models. However, the gap appears to be rapidly narrowing, and even reversing (as per the depreciation rates used to calculate capital costs in Figure 12). As the technology has matured, the number of models available has increased and public awareness and perception has improved, electric cars are holding greater value for longer – with the Tesla Model 3, launched in 2017, commonly cited as having one of the lowest depreciation rates of any car on the market (Blackley, 2020). At the same time depreciation rates for diesel cars in particular have increased as concerns over local air pollutant emissions, and measures to tackle them (including emission-based charges), spread in the wake of the 'Dieselgate' scandal in 2015.

The final two columns of Figure 12 illustrate that in this example, removing subsidies and increasing the depreciation rate of electric cars to that of diesels would substantially increase capital costs, but the total TCO of the electric option would remain beneath that of the diesel option, and comparable to the gasoline option. This is mainly due to EVs' substantially lower fuel and maintenance costs. EVs are more energy efficient than ICE vehicles, and electricity prices tend to be lower than gasoline and diesel prices for the same amount of energy. They also require less maintenance in general, due to their relative simplicity and fewer moving parts.

In addition, many countries around the world levy registration and/or annual ownership taxes on cars based on their CO_2 intensity. In the UK, zero-emission cars pay a zero-rate on both (OLEV, 2018), while registration taxes reach £2,175 (around USD 3,020) for cars with a CO_2 intensity exceeding 255 gCO_2/km. Most non-electric cars pay an annual ownership tax of £150 (around USD 210) (UK Government, 2020b). As illustrated by Figure 12, such taxes are relatively minor in the UK for relatively efficient ICE vehicles, but annual ownership taxes in particular are significant.

The overall cost-competitiveness of EVs also depends on use patterns and jurisdictions with different policy landscapes. Beyond just passenger cars, EVs have increasingly obvious advantage for travel patterns of extensive but localized use – such as local delivery vehicles (ITF, 2020).

Yet, almost irrespective of use and geography, relative TCOs are likely to increasingly favour electric cars over ICEVs as production costs decline (see next section), electric cars gain greater market share at the expense of ICEVs, and measures to tackle local air pollutant and CO_2 emissions continue to spread and become more stringent.

21 In the UK subsidies are available for cars that have a CO_2 intensity of less than 50gCO_2 / km and can travel at least 112km at zero-emissions, at a rate of 35% of the list price, up to a maximum of £3,000.

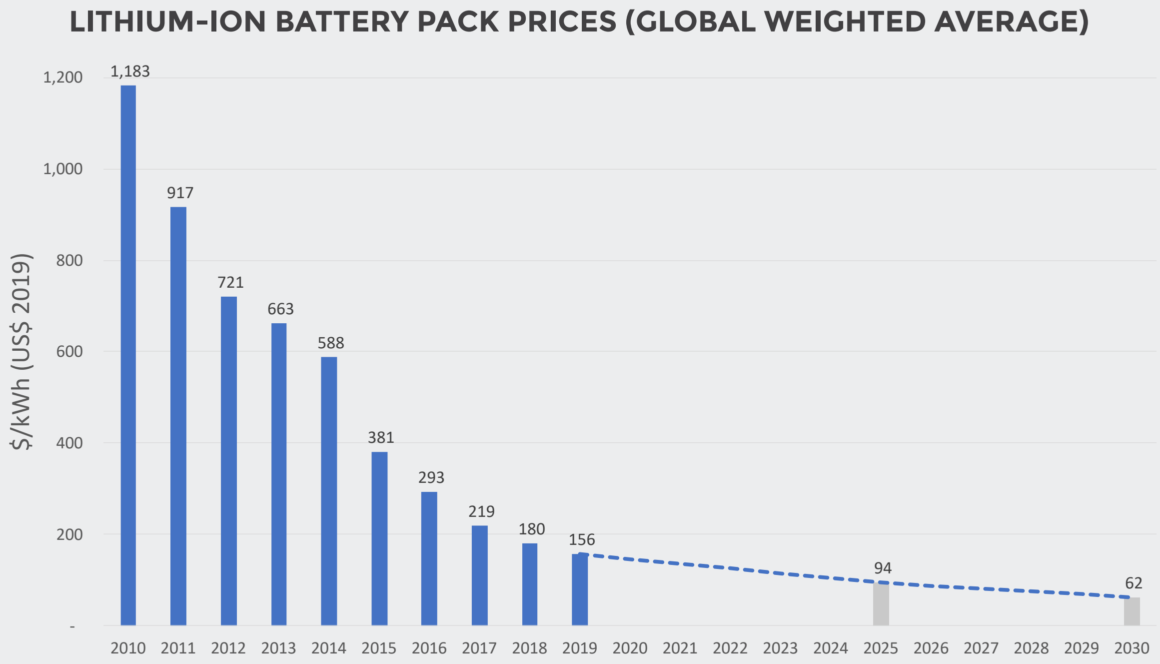


Figure 13: Lithium-ion battery pack prices (global weighted average) 2010-2030. Source: Bloomberg NEF (2019a)

3.2 BATTERY PRICES

Battery prices fell by 87% from 2010 to 2019, driven by a combination of economies of scale, increasing battery capacity and improvements in battery chemistry. Such trends are likely to continue to drive down battery prices, making the cost of producing EVs increasingly comparable with ICE vehicles in many segments within the next five years.

The single biggest reason why EVs cost more to produce than comparable ICE vehicles is the higher cost of the electric powertrain. In 2017, around two-thirds of the electric powertrain costs were from the battery pack, which in turn represented around a quarter of the cost of the entire vehicle (Lutsey and Nicholas, 2019). Developments in battery costs are therefore central to prospects for relative capital costs. Battery costs have fallen dramatically in recent years. Figure 13 illustrates the 87% reduction in lithium-ion battery pack costs experienced between 2010 and 2019; from $1,183/kWh to $156/kWh. This was driven by a combination of economies of scale as deployment grew, increasing battery capacity, and improvements in battery chemistry to improve energy density. However, the values quoted in Figure 13 are the global weighted-average, and there is substantial price variation. The lowest prices are generally paid by the largest manufacturers focusing on pure EVs with long ranges that require large battery capacities (such as Tesla), while higher prices are paid by low volume manufacturers focusing on plug-in hybrid EVs (PHEVs) (IEA, 2020c).

A battery pack price of $100/kWh is generally seen to be the point at which EVs begin to reach parity with the purchase price of ICE vehicles (BNEF, 2019b). Figure 13 also illustrates future projections of average battery pack prices for 2025 and 2030, as projected by Bloomberg New Energy Finance. They project the $100/kWh threshold to be surpassed by 2025, with average prices reaching $94/kWh, and to be well below this by 2030, at just $62/kWh. However, there is likely to be substantial variation in geographies and vehicle segments for when price parity is reached in practice; beginning with large cars in Europe, where it may be achieved as early as 2022, to after 2030 for small vehicles in India and Japan, where average purchase prices for comparable ICE vehicles are very low (BNEF, 2020).

The range from EVs remains lower than equivalent ICE vehicles (and obviously ICE vehicles benefit from a well-established network of filling stations, compared to charging networks discussed in the next

section). However, along with declining costs, battery performance and associated range has improved. The Tesla 3 range at full charge is around 480 km (EDF, 2020b). The more mid-range models have a more modest range – typically between 160 and 320 km in real world conditions (EDF, 2020a) – though the Chinese BYD and GAC models claim ranges exceeding 380 km (Kane 2018; 2019). All these reflect a trend of continuing and rapid improvement.[22]

Further reductions in battery pack prices, and improved ranges, are likely to be reached largely through a continuation of existing trends. Economies of scale will continue to grow with deployment, supported by reductions in manufacturing costs as equipment and techniques improve and domestic supply chains begin to develop, reducing the costs involved with importing battery cells. Battery pack sizes are likely to continue increasing as technology develops and as sales increasingly focus on pure EVs and less on PHEVs, with capacities increasing from an average of 48-67 kWh in 2019, to around 70-80 kWh by 2030 (with a range of 350-400 km). Energy densities are likely to increase as the next generation of lithium-ion batteries begins to enter the market, and battery pack designs are likely to be simplified and become increasingly standardized, further reducing material and manufacturing costs and allowing scaling for different vehicle segments and hence to other transportation modes (BNEF, 2019b; 2020).

3.3 TOTAL EMISSIONS OF OWNERSHIP (TEO)

Another determinant of the pace of transition will be environmental. In particular, with climate change as a key motivation, due attention is required to the Total Emissions of Ownership (TEO) in different contexts.

As shown in Figure 2, the dominant factor is the emissions associated with electricity production. Even at the current global average carbon intensity, EVs already have lower emissions than ICE vehicles, but the margin is modest. In systems still dominated by coal power generation, the benefit may all but disappear. However, as charted in our previous report, electricity

22 Both Chinese models claim ranges well in excess of 380 km, though (as for some other models), with some uncertainty about the conditions applicable – 'real world' ranges often tend to be lower.

globally is now on a trajectory of slow but accelerating decarbonization. Our inverse S-curve projections – consistent with the pace of solar and wind growth in particular, to 20-40% of generation by 2030 - suggest that by then, carbon intensity would have fallen from around 500 to around 260 gCO_2/kWh, and would then be falling steeply – globally, and in most regions.

EVs would be expected to run for at least a decade, so such forward projections are relevant even to purchases today. Moreover, in some cases they may be either charged directly from isolated renewables, or able to schedule charging at times of high renewables output or otherwise low grid carbon intensity 'at the margin'. Detailed calculations are beyond the scope of our report, but applying the analysis of our electricity transitions report to the data in Figure 2, it is plain that – notwithstanding regional differences - electric vehicles operating in 2030 would have a much lower overall TEO than combustion engines in almost circumstances, and their emissions advantage would only grow further over time.

In all, therefore, EVs seem to be on an inexorable trend to greater advantages in both cost and environmental advantage. This should maintain rapid growth. How fast, and how far it extends, however, will depend on additional factors, considered in our final section.

SECTION 4: SUSTAINING AND EXTENDING THE TRANSITION

Trends in the share of EVs in the total stock and sales of passenger cars are positive and potentially on course for Paris-consistent benchmarks. Economic indicators are also encouraging, with purchase costs of EVs falling, largely due to falling battery costs, and the total cost of ownership already being lower than that of ICE vehicles in some situations.

However, there are also systemic issues which if not adequately addressed could slow deployment and constrain the pace and scale of the transformation. The academic literature underlines that purposive transitions are complex processes, requiring multiple policies and coordination. This section examines these factors, highlighting particular issues and examples of national progress, in three main areas:

- Charging infrastructure and system integration
- Purchase prices and lifetime costs
- Co-development of supply and demand

Annex I includes supporting data on deployment indicators by country.

4.1 CHARGING INFRASTRUCTURE AND SYSTEM INTEGRATION

Installations of publicly accessible recharging equipment have grown at an average of 82% per year from 2010-2019. Increasing range of EVs may render ubiquity of charging points less of a constraint. Integration of mass EV charging with power systems creates challenges, but also opportunities. Further attention is required to policies that support and coordinate infrastructure roll out, and enable integration of EVs within electricity systems.

4.1.1. Charging infrastructure

The global availability of publicly accessible recharging equipment has grown explosively, with an average annual growth rate in installations of 82% per year between 2010 and 2019 (Figure 14). The global total number of publicly accessible chargers in 2019 was estimated at over 860,000, with particularly rapid growth in China (Figure

ELECTRIC VEHICLE PUBLICLY ACCESSIBLE CHARGING POINTS

a) Publicly accessible charging points by country

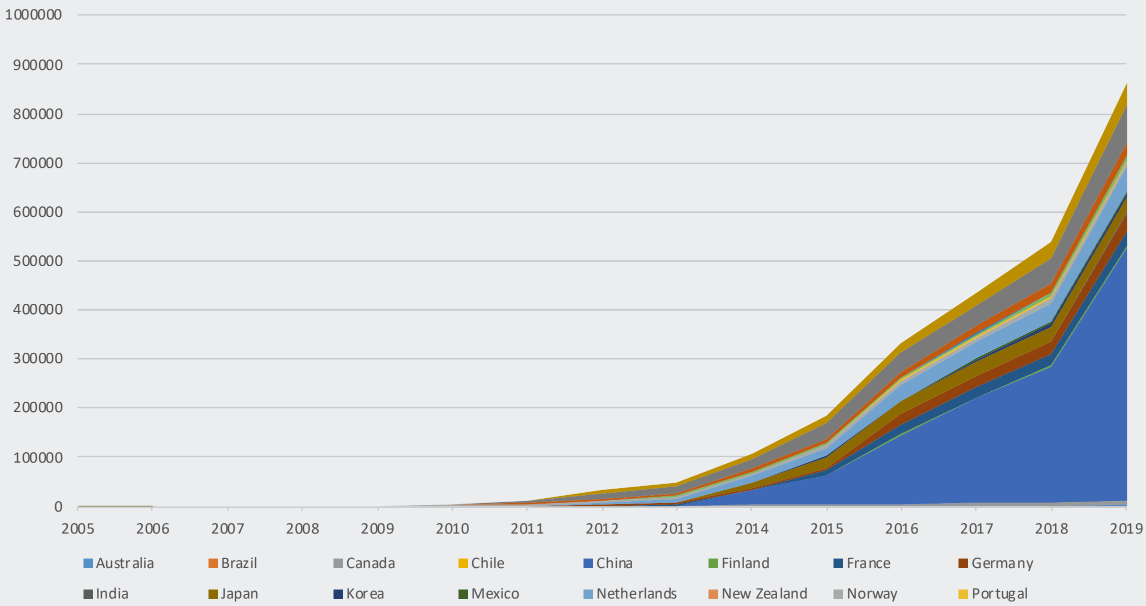


Figure 14: Total global publicly available EV chargers, 2010-2019: (a) total by country; (b) fast and slow chargers. Source: IEA (2020c) Statistical annex

ELECTRIC VEHICLE PUBLICLY ACCESSIBLE CHARGING POINTS

b) Fast and slow chargers

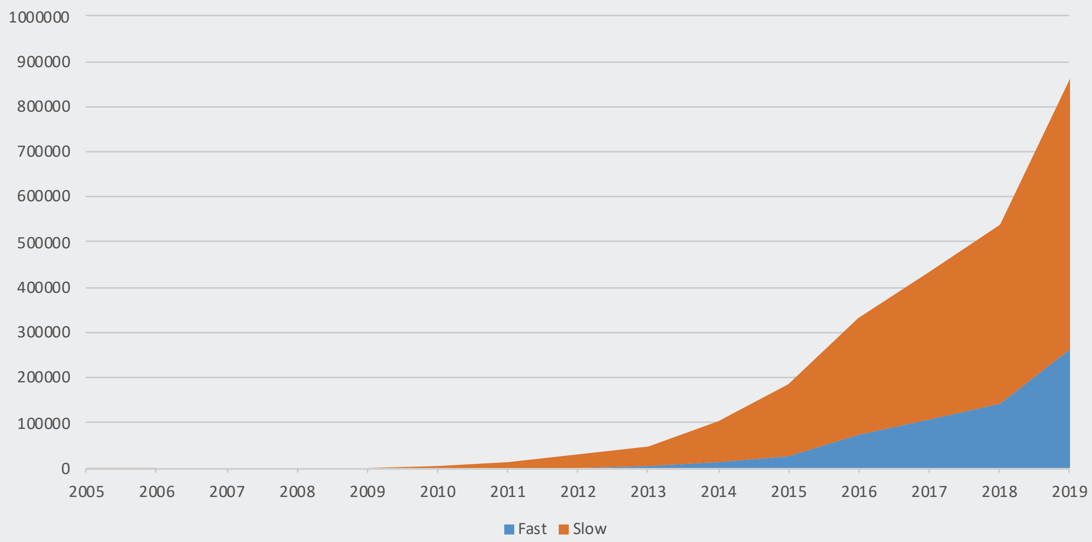


Figure 14: Total global publicly available EV chargers, 2010-2019: (a) total by country; (b) fast and slow chargers. Source: IEA (2020c) Statistical annex

14a). Whilst earlier roll-out of public charging points was entirely based on slow chargers, since 2013 the number of fast chargers has been increasing rapidly (Figure 14b). The ability to charge in minutes rather than hours has a significant impact on the convenience of EVs relative to ICE vehicles. However, the IEA estimate that publicly accessible chargers accounted for just 12% of the total number of light duty vehicle chargers (IEA, 2020c)

4.1.2. Effect of charging infrastructure on EV numbers

The absolute numbers both of publicly available chargers and total numbers of EVs in any given country, will be strongly affected by the size of the country and the market for new cars. Absolute numbers are important for considering the global dynamics of the industry, but country and regional indicators are also vital. China leads in both number of EVs deployed as well as and the number of publicly available chargers, followed by the US at some distance (see Appendix 1 for details).

Appendix 1 shows that the relationship between public charging infrastructure and market share of EVs is not straightforward. Norway has by far the highest share of EVs – over 50% – with a low density of public charging points. This reflects not only the country's wealth, but also its space, with most EV owners being able to charge at home, and many others have reserved charging places at work or elsewhere. These luxuries do not exist in most other countries. The EU's Alternative Fuels Infrastructure Directive (IEA, 2020c) recommends a benchmark density for public charging points of 1 per 10 EVs – a level which, interestingly, is at present exceeded mainly by some Latin American countries (Appendix 1).[23]

An important factor is the driving behaviour that EVs are expected to enable. Vehicles primarily dedicated to a within-range daily work commute, with charging available either at the home or workplace, will rarely if ever require a publicly available charging point. Such availability will also be affected by wealth, culture and urban design decisions – for example, whether residential buildings are built with private off-road parking spaces, or whether vehicle owners use unreserved street parking, as in Norway. Where fewer owners can park on their own property or reserve parking spaces the need for public infrastructure is much greater. Users with longer or less predictable travel would benefit from a correspondingly more comprehensive public charging infrastructure..

As a shared public infrastructure, there is a rationale for governments to become involved in the development of charging infrastructures, and many have done so. A lack of sufficient interoperability could be a barrier to wider uptake of EVs, and governments also therefore have a role in coordination, as explained in Box 3.

23 If improving battery technologies continue to deliver greater range, this may somewhat reduce the density of public charging infrastructure that might be required. Nonetheless, to achieve a level of convenience, flexibility and range coverage that would make EVs competitive with the full ranges of ICE capabilities, a coordinated and interoperable public fast charging infrastructure would be required, probably with at least as much coverage as currently provided by gasoline and diesel filling stations on major highways.

Box 3: Policies to address charging infrastructure and system integration

In Norway, a government financed program was launched in 2017 to establish 'at least two multi-standard fast charging stations every 50 km on all main roads in Norway' (Norsk Elbilforening, 2020).

There are currently around 165,000 publicly accessible charging points in the EU; the European Commission projects the need for 1 million by 2025. The Alternative Fuels Infrastructure Directive requires EU member states to set deployment targets for 2020, 2025, 2030, indicating a target ratio of 1 charger per 10 electric cars. The Energy Performance of Buildings directive 2018, includes requirements for new and renovated buildings to include EV charging infrastructure (IEA, 2020c).

France is targeting 100,000 publicly accessible chargers by the end of 2021, and Germany has introduced provisions for charging services to be provided at all petrol stations in the country. India's Bureau of Energy Efficiency has established targets for 1 charger per 3 km_2 in cities, 1 charging station per 25km on both sides of highways, and 1 fast charger per 100 km on highways, with funding provided under the Faster Adoption and Manufacturing of Electric Vehicles (FAME) scheme. The Japanese government subsidises the installation of charging infrastructure, providing between one half and two-thirds of the cost (IEA, 2020c).

In the US, the federal charging infrastructure tax credit covers up to 30% of the installation cost of new charging infrastructure. The proposed Electrify Forward Act would update building codes to encourage EV charging, and require states to consider measures to roll out EV charging stations. 42 US states have policies to help financing of installing or operating infrastructure deployment (IEA, 2020c).

Canada is aiming to develop a coast-to-coast network of fast charging. The Canadian government has also provided funding for charging in public places, workplaces and commercial areas, and supports the development of codes and standards.

China is aiming to shift from subsidizing vehicles to supporting infrastructure roll out, including publicly accessible charging, private charging and company based charging (IEA, 2020c).

Chile's Ministry of Energy is responsible for regulating the inter-operability of charging infrastructure. In India, the Bureau of Energy Efficiency is the central agency with responsibility for the roll out of public charging infrastructure, also providing guidance on specifications (IEA, 2020c).

Coordination may also be required with operators of power networks and systems. For example, the deployment of electric buses in Santiago and Shenzhen required distribution network upgrades, calling for coordination with local distribution network companies (IEA, 2020c).

Charging requirements are also affected by the range of EVs. As discussed in Section 3, battery technology improvements are continuing to increase the ranges achieved by successive generations of EVs, typically now between 320-480 km for many models, which decreases the pressure on charging availability.

4.1.3 Energy demand from the electricity system

EV recharging can create challenges, as well as opportunities, for the operation of the power systems from which they draw their energy. Widespread electrification of transport could add significantly to overall energy demand from the electricity system. At present the impact of EVs on electricity demand is small. IEA calculated that in 2019, EVs had begun to register on China's grid, accounting for 1.2% of China's total electricity consumption; however, the share in other major markets was below 1% (Table 5). Under IEA scenarios, by 2030 EV electricity demand could be 3% of total electricity demand in China, and 4-6% in the US and Europe (Table 5). By 2050, electricity demand from light duty vehicles overall could account for 13-26% of total electricity demand in the United States (Fox-Penner et al. (2018)).

Table 5: Share of electricity consumption attributable to EVs by region and scenario, 2030. Source: IEA (2020c) p. 171

Country / Region	2019	Stated policies scenario, 2030[24]	Sustainable development scenario, 2030[25]
China	1.2%	3%	3%
Europe	0.2%	4%	6%
India	0.0%	2%	3%
Japan	0.0%	1%	2%
United States	0.1%	1%	4%

Potentially even more significant than the overall increase in energy demand on the electricity system could be the increase in power demand at peak times. If large numbers of EV users chose to recharge their vehicles at the same time, this could create an expensive 'peak', requiring additional generation capacity that would be left on standby outside of the peak demand period – particularly if this coincided with existing demand peak periods, such as (in many systems) the early evening.

Figure 15 underlines the importance of smart charging. It shows the potential impact of EV charging on peak electricity demand in 2030 in selected regions and countries. If EV demand coincides with evening peak it could add typically around 4% (China) to around 10% (EU) to peak demand. However, if EV charging is spread, including through the night, the impact on peak demand is much lower – an estimated 1% (China and India) to 3-4% in the US and the EU (IEA (2020c) p. 233).

The ability to optimize charging patterns is therefore valuable to the successful incorporation of large numbers of EVs into power systems around the world. Moreover, EVs could also help support power systems that have high shares of variable renewable energy. The ability to shift EV charging could be used to move the load into periods of high renewable output andaway from periods of low output. The ability for EVs to feed electricity back into the grid (vehicle-to-grid, V2G) could be used for frequency response or to balance the system at times of low demand. The integration of EVs and electricity systems could therefore potentially add value to EVs, whilst bringing effectively a new and major source of cheap storage and associated dynamic regulatory capacity for power systems.

24 The Stated Policies Scenario, used in the IEA publications, Energy Technology Perspectives, and the World Energy Outlook, aims to illustrate the likely consequences of existing and announced policy measures.

25 The Sustainable Development Scenario is a scenario used in the IEA publications, Energy Technology Perspectives, and the World Energy Outlook, to illustrate a pathway that: ensures 'universal energy access for all by 2030'; brings about 'sharp reductions in emissions of air pollutants'; and meets 'global climate goals in line with the Paris Agreement' (IEA, 2020b)

SHIFTING EV CHARGING PRACTICES TO AVOID PEAK HOURS COULD REDUCE THE CONTRIBUTION OF EVS TO PEAK DEMAND TO LESS THAN 4%.

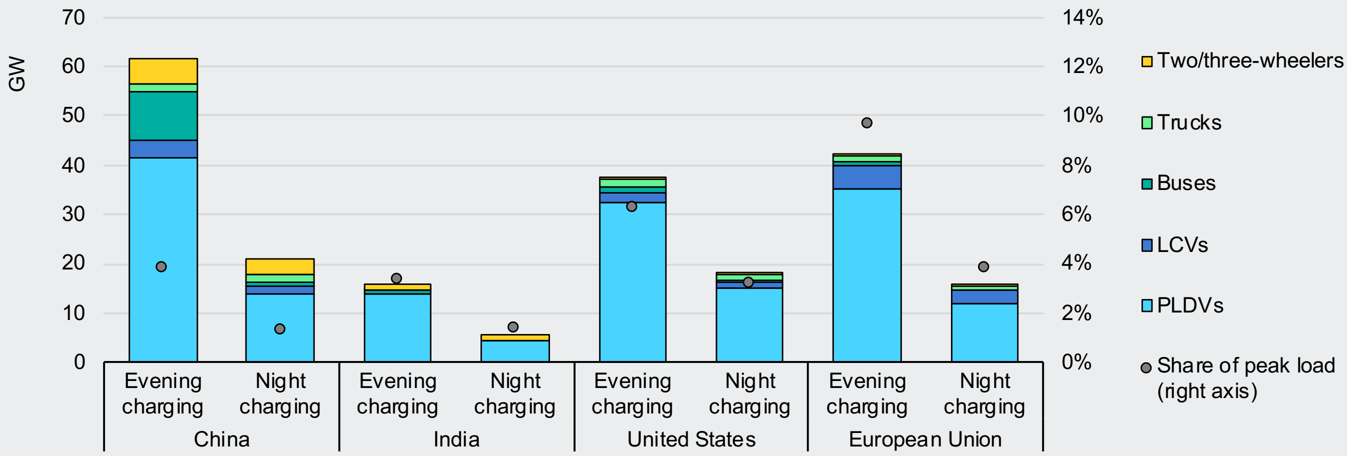


Figure 15: Contribution of EVs to hourly peak demand by country / region in the evening and night charging cases in the Sustainable Development Scenario, 2030. PLDVs = passenger light duty vehicles; LCVs = light-commercial vehicles. Source: IEA (2020c) p. 233

Policies to support such integration can take the relatively simple form of using on- and off-peak pricing periods to encourage EV charging to take place away from peak periods. More complex from a regulatory point of view, but with much greater potential rewards for system operation and overall costs, would be dynamic pricing coupled with smart grid technologies. These could enable EVs to play an active role in system balancing and other services such as frequency response, within parameters that still allows them to perform their primary function as a vehicle. Market structures that reward EV owners for allowing the batteries in their vehicles to be used for such system services, would be crucial to unlock this potential (Brown, 2014, Foley et al., 2013, Leiva et al., 2016).

4.2 HARNESSING AND ACCELERATING THE GROWING ADVANTAGE IN LIFETIME COSTS

4.2.1. Tax exemptions

Besides infrastructure, public policies which enhance the financial attractiveness of EVs for consumers have been crucial. Norway, the most successful country for EVs in terms of market share (Appendix 1) in fact largely avoided direct subsidy of EVs, focusing instead on exemptions to taxes that apply to more polluting vehicles. Principal amongst these measures are the exemptions for ZEVs (including EVs) from various purchase taxes: VAT, as well as weight-, CO_2- and NO_x-based taxes.

Table 6 shows how these taxes can raise the purchase price of an ICE vehicle above that of a similar ZEV, creating a clear incentive for the ZEV.

Table 6: The impact of the Norwegian car tax system on the retail prices of ICE vehicles and ZEVs - the case of the Volkswagen Golf and the Volkswagen e-Golf. Source: Norsk Elbilforening (2020)

	Volkswagen Golf	**Volkswagen e-Golf**
Import price	22 046	33 037
CO_2 tax (113g/km)	4 348	-
NO_x tax	206	-
Weight tax	1 715	-
Scrapping fee	249	249
25% VAT	5 512	-
Retail price	**€ 34 076**	**€ 33 286**

The Norwegian approach was enabled by the range and level of purchase taxes already applied to internal combustion engine vehicles, which cannot be simply replicated elsewhere. In practice, many governments are adopting a mix of subsidies, rebates and exemptions on purchase taxes to lower the initial purchase cost barrier.

Box 4: Finance-related policies: reducing the cost of ownership and purchase

In Canada, point of sale incentives and tax credits support the purchase of ZEVs. Germany and Japan provide direct purchase subsidies, with Japan also offering exemptions on purchase taxes. In Italy and France, purchase subsidies are linked to scrappage schemes for old vehicles (IEA, 2020c), and in Norway compensation is offered for scrapping a fossil-fuelled van if it is replaced with a zero-emission van (Norsk Elbilforening, 2020). The US provides tax credits for PHEVs and BEVs, and 16 US states provide subsidies, tax credits or waivers that support the purchase of EVs (IEA, 2020c). In the UK, EVs are exempt from vehicle excise duty payable on purchase (OLEV, 2018).

As well as the sales mandates described in Section 4.3.2, China's New Energy Vehicle (NEV) program also provides subsidies, related to driving range, efficiency and energy density of the vehicle. In 2019 the driving range threshold was raised to a minimum of 250 km in 2019, and the subsidy level was reduced by 50%. The aim is to phase out subsidies by 2022 (IEA, 2020c).

In several countries including Germany there is a price limit to the vehicles that qualify for subsidies, to avoid subsidizing luxury purchases. India's Faster Adoption and Manufacturing of Electric Vehicles (FAME) program provides purchase incentives for buses, 2 and 3-wheelers, PHEV and HEV cars. For cars the maximum sales price to which the subsidies can apply is USD 19,900 – however this makes most models ineligible (IEA, 2020c). In contrast, the UK has not placed a price limit on ZEVs qualifying for vehicle excise duty exemption, and furthermore has recently exempted ZEVs from the supplementary tax which had applied to all vehicles with a list price above £40,000 (around USD 56,000) (UK Government, 2020a).

Policies can also reduce the ownership costs of electric vehicles – Germany, Italy and Japan offer exemptions or reductions in annual vehicle taxes for EVs (IEA, 2020c), as does the UK (OLEV, 2018) and Norway (Norsk Elbilforening, 2020).

4.2.2. Taxes and charges

Existing taxes and EV policies can also affect the relative operating costs of different kinds of vehicles. Many countries charge excise duties on gasoline, often ostensibly to reduce oil import dependence and/or fund road-building. EVs in many countries are exempt from such duties. In the UK, electric vehicles in practice also benefit from a reduced rate of value added tax (VAT) on electricity, and in London, from exemptions from the congestion charge, justified since a key aim of the charge was to improve air quality as well as reduce congestion (OLEV, 2018). These measures provide incentives to users of EVs relative to users of ICE vehicles. Norway further supports the operational costs of EVs through a '50% rule' under which charges levied on EVs for the use of toll roads, ferries and parking spaces may be no more than 50% of the charges applied to fossil fuelled vehicles in each case. Regions are also allowed to grant EVs access to bus lanes (Norsk Elbilforening, 2020). Pakistan is intending to encourage the adoption of electric trucks (IEA, 2020c) by subsidizing the electricity provided at public charging points.

4.2.3. Issues in financial support: equity and financial sustainability

As market shares of EVs increase, tax exemption policies may create challenges for public revenue collection, and may raise fairness concerns. Where the fuel tax is explicitly a tax on an environmental externality (as for example with Norway's CO_2 and NO_x taxes) then it is appropriate that EVs should avoid it. However, fuel or vehicle taxes may also be used to collect revenue for maintenance of roads and related infrastructure, and VAT contributes generally to public spending. Whether EV users should avoid taxes which contribute more generally to social welfare could raise questions of fairness, especially if EV ownership is skewed towards wealthier social groups. Appropriate principles are particularly complex when excise duties combine different rationales and uses - for example, to reduce oil import dependence but when the revenue is also used to fund railways, or the maintenance of road infrastructure which is also used by EVs (though to the extent EVs tend to be lighter, they might also reduce maintenance requirements).

In some US states this issue is being addressed by adding an additional fee to the standard annual registration fee, payable by owners of EVs or PHEVs, in order to recover costs of highway use (Hartman and Shields, 2020). Alternative approaches could be to link more closely revenue collected for the purpose of highway maintenance, to vehicle kilometers travelled.[26]

While the purchase cost of EVs is still typically higher than conventional vehicles in the absence of subsidies or the effects of taxes, as noted they may already be lower cost in terms of the total cost of ownership. This naturally suggests policy options to help spread the upfront cost over the lifetime of the vehicle, paid effectively alongside the lower operating cost. Policies can support alternative business models or payment schemes, such as leasing or spread payment arrangements, accompanied with patient financing to reduce interest rates. In India, for example, income tax exemption is available on loans used for EV purchases (IEA, 2020c).

Policies that support car sharing 'clubs' may also have the potential to capture this benefit, as in such business models members pay a relatively small subscription fee and rent vehicles by the hour, removing from the consumer the burden of the upfront capital cost. Thinking further ahead, the shared transport economy could evolve further if new automotive technologies such as autonomous capabilities could be integrated with electric vehicles. These could evolve into autonomous shared occupancy vehicles (Fox-Penner et al., 2018) or 'robotaxis' (BP, 2020), that could then integrate with more bulk forms of transport, enabling a door-to-door shared transport system. Such a system could in turn reduce the importance of the privately owned car and its upfront capital cost as a barrier. The full evolution of such an integrated shared transport vision would likely have a significant role for private sector innovation, but also for policy to address regulation and coordination of IT and other infrastructure.

4.3. CO-DEVELOPMENT OF SUPPLY AND DEMAND

Several countries have long-term targets for the shares of EVs in vehicle fleets that are Paris-consistent at the national level (assuming that their electricity supply systems are simultaneously decarbonized), and support the deployment of EVs through measures including direct grants, tax exemptions or public procurement. However, at the global level, ZEV pledges sum to only one third of passenger cars by 2060.

The academic literature on purposeful system transitions underlines that a clear direction, as well as coordination, are vital to a smooth and efficient transition; and that regulation, combined with financial incentives, can play important roles.

4.3.1. High-level targets

High level decarbonization targets can have a useful role in clarifying the long-term direction of travel, giving signals to manufacturers of governments' commitments to supporting zero emissions vehicles, and increasing their confidence in the future existence of a market. Such targets can encourage manufacturers to invest in technology development and in scaling up production.

The European Green Deal seeks a 90% cut in transport emissions by 2050 (EC, 2019b). Germany's Climate Action Program aims to reduce emissions from the transport sector by 40-42% by 2030. The Netherlands' National Climate Agreement pledges a 30% reduction in CO_2 emissions from inland and continental transport by 2030 relative to 1990 (IEA, 2020c).

There are a number of national level targets for the share of zero emission vehicles (ZEVs) or EVs in vehicle fleets or in vehicle sales by specified future years, or of commitments to ban sales of ICE vehicles by a specified future year. In Norway, all new cars and light vans sales are to be ZEVs by 2025. Several countries including Denmark, Iceland, Ireland, the Netherlands and most recently the UK have adopted targets to 100% sales of zero emissions vehicles

26 Such linkage could be achieved through increased use of toll-roads; or by instituting a "vehicle kilometers travelled" tax to apply to all vehicle types (Boesen, 2020), and which could be informed by periodic odometer readings, for example taking place at annual vehicle tests or re-registration. There are advantages and disadvantages to each approach; but overall it is important that efforts to incentivize EVs should also balance the principles of fairness during the transition.

by 2030 (IEA, 2020c), sometimes expressed as outright bans on ICE car sales as in the UK. Canada aims to achieve 100% light duty ZEV sales by 2040, and Cabo Verde, Costa Rica, Japan, Mexico and Sri Lanka all have 100% either stock or sales targets for dates ranging between 2030-2050 (IEA, 2020c).

The impact of existing pledges of this kind on car market shares are summarized in Figure 16. The current pledges would be equivalent to an overall global market share for EVs and ZEVs of 33%. Whilst this would be a sizeable EV market, as yet, globally this falls far short of the close to 100% share of EVs needed in the global car fleet by 2050.

4.3.2. Push and Pull: policies that constrain conventional options or mandate EV market share

Long-term targets give a direction of travel which may increase the confidence of automotive manufacturers to invest in and develop new vehicles, but do not in themselves directly mandate or incentivize EVs, or other ZEV technologies. Policies such as emissions standards and mandates can exert more direct impact.

Emissions standards, if strict enough, can create a market for EVs and other ZEVs by prohibiting or restricting the use of ICE vehicles. EU emissions standards are continuing to be tightened, and from 2021 the fleet-wide average target for new cars will be 95 gCO_2/km. A 'super-credits' system gives increased credit to manufacturers for introducing zero- and low-emission cars emitting less than 50 gCO_2/km (EC, 2020b). Beyond this, from 2025 the fleet wide average standard will be reduced by 15% from the 2021 level, and by 37.5% from 2030 (EC, 2020a), i.e. to 59gCO_2/km. This is below the typical emissions intensity even of current hybrid vehicles, and thus will likely require manufacturers to increase their supply of ZEVs to bring down their fleet wide average.

MARKET SHARES OF ELECTRIC OR ZERO EMISSION CARS, 2030-2060, BASED ON CURRENT PLEDGES AND TARGETS

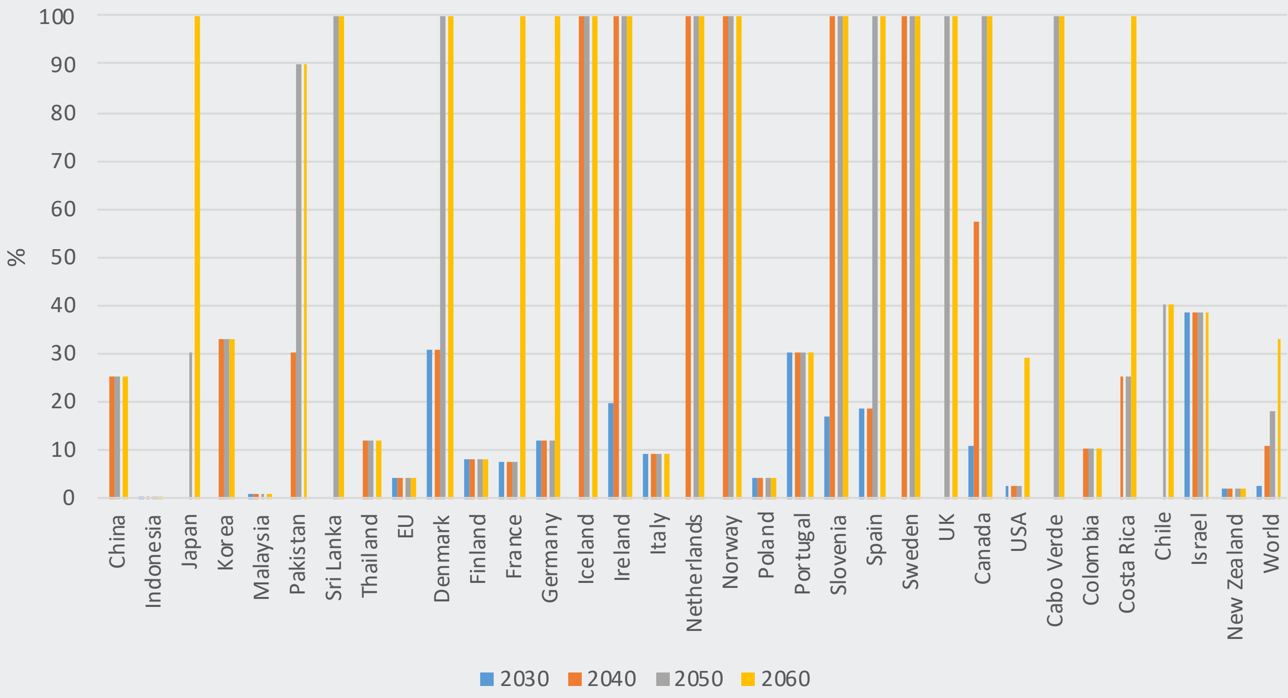


Figure 16: Based on pledges listed in Table 2.1 of IEA (2020c). Pledges expressed as shares of new sales are assumed to translate to the same share of stock ten years later. Total passenger stock for each country calculated from OICA (2020b) and (2020a) in order to convert shares into numbers of vehicles, and vice versa, based on 2019 stock data. World market share calculated from the sum of the number of vehicles implied by each country's pledges, as a percentage of the total global passenger cars in 2019 from OICA (2020a) and (2020b). USA share is based on the 100% ZEV pledge of 10 US states: California, Connecticut, Maryland, Massachusetts, New Jersey, New York, Oregon, Rhode Island, Vermont and Washington, and expressed as the share of the total US car stock. State-level data for total vehicle numbers in these US states based on private and commercial (including taxicabs) automobiles, from FHWA (2010).

Japan, with traditionally tough vehicle efficiency standards, also has a 2050 goal to reduce GHG emissions per km by 80% across all Japanese manufactured vehicles on a 'well to wheel' basis – again, clearly requiring the widespread use of ZEVs (IEA, 2020c).

Another approach is to force EVs into the market through sales mandates placed on retailers. In China the New Energy Vehicle (NEV) program covers EVs, plug-in hybrid EVs (PHEVs) and fuel cell EVs (FCEVs) and includes a credit mandate policy imposed on vehicle suppliers. Sales of all types of NEVs generate credits for suppliers to reach their mandated level, however FCEVs typically attract more credits than EVs and PHEVs (IEA, 2020c).

Emissions standards and restrictions can also be aimed at the users of vehicles, which could drive consumer demand for lower emission vehicles. Various Chinese cities operate with traffic restrictions measures to which EVs are exempt, which may help to encourage their adoption, with the island province of Hainan targeting 100% EVs by 2030. In France the 2019 Loi d'Orientation des Mobilités (Mobility Orientation Law) mandates the establishment of low-emission zones in high pollution areas by the end of 2020 (IEA, 2020c).

4.3.3. Policies that invest in technology or build up supply chains

The Paris-consistent benchmarks for EV shares of stock and sales, and the S-curves projected towards them, create a picture of a rapid scale up in manufacturing over the coming decades. This will involve a large number of jobs, particularly attractive in industrial areas faced with the unemployment impacts of a transition away from fossil fuels. The previously-discussed policies for supporting and enabling the growth of EV markets would have an impact on manufacturers' decisions about locating their plants. Additionally, attention to skills development and transitioning of skills from fossil fuel automotive sectors, securing supply chains and investing in related infrastructure, and playing to national strengths but also seeking cooperation where beneficial, are all potentially useful policy areas for capturing the benefits of the huge transition in prospect.

Box 5: Policies to stimulate supply

In China, policies aimed at strengthening domestic manufacturing of low emission vehicles with a view to the global export market, include a ban on new ICE vehicle manufacturing companies that do not meet certain performance requirements, and requirements that new energy vehicle manufacturers must have an established R&D group, own EV related patents and offer after sales service (IEA, 2020c). India's National Mission on Transformative Mobility and Battery Storage aims to build a manufacturing supply chain over the period 2019-2024.

In 2017 the European Commission set up the European Battery Alliance, an industry coalition aiming to establish a competitive battery industry in Europe (EBA, 2020). The Electrify Forward Act proposed in the US House of Representatives, would aim to accelerate domestic manufacturing, and modify and reauthorize a manufacturing grant and loan program (IEA, 2020c).

Chile is estimated to have potentially half the global reserves of lithium. It has undertaken measures to promote the domestic lithium industry including offering lithium resources at preferential rates in order attract battery manufacturing activities (IEA, 2020c).

4.3.4. Beyond individual passenger vehicles: buses

Although passenger private cars are a key market for EVs, other market segments are also important and may have additional attractions for policy support.

Buses are potentially a promising mode for electrification, motivated particularly by the air quality impacts of diesel buses. There are about half a million electric buses globally, with China having deployed the most. However, electric buses have substantially higher capital costs than ICE buses, and despite typically lower running costs, total costs of ownership are often still higher (IEA, 2020c). As such, "e-buses" require policy support. Key examples include:

- In Shenzhen, China, bus electrification is pursued via fleet mandates and purchase subsidies, in partnership with local manufacturer BYD who provide the buses and their maintenance (IEA, 2020c).
- Santiago de Chile has established stringent emissions standards for buses, and is the city with the largest electric bus fleet outside of China. Deployment has also been supported by partnerships between the bus operators and the energy company which provides charging infrastructure, as well as with BYD, which manufactures most of Chile's buses. One of the city's main bus routes is now supplied 100% by electric buses (Intelligent Transport, 2019). Chile has a target to electrify 100% of public transport by 2040 (IEA, 2020c).
- Kolkata procures electric buses with purchase subsidies under India's Faster Adoption and Manufacturing of Electric Vehicles (FAME) program. The state-owned transport undertaking is responsible for both buses and charging infrastructure. Nagpur and Delhi are also procuring electric buses under the FAME scheme (IEA, 2020c).
- European examples include the Netherlands, where all new public bus sales are intended to be electric by 2025, leading to the full stock being electric by 2030 (IEA, 2020c); and the Helsinki Region Transport authority which has promoted electric buses by establishing minimum deployment levels for electric buses as part of tenders with bus companies, with separate tenders for the provision of charging infrastructure (IEA, 2020c).
- In North America, California's Innovative Clean Transit Regulation aims for a 100% zero emission bus fleet. The government of Canada aims to work with the provinces and territories towards the purchase of 5000 zero emission school and public transit buses over five years.

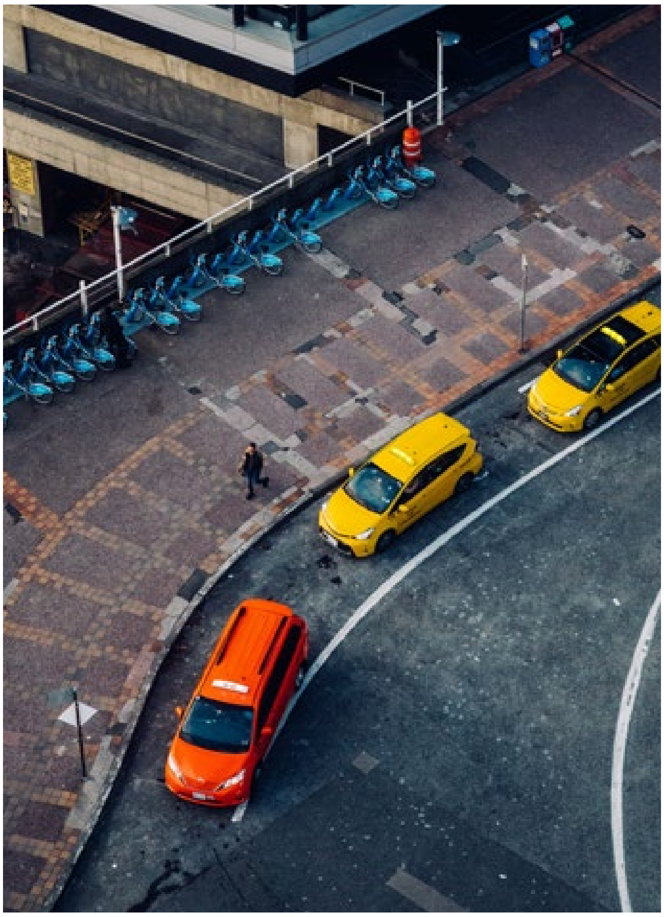
4.3.5. Beyond individual passenger vehicles: taxis, fleet vehicles, trucks, two- and three-wheelers

Municipal services. In addition to buses, public sector fleet vehicles such as waste collection trucks offer wider opportunities for bulk procurement, which can help to reduce costs. Further, the reduction of air pollution caused by such vehicles, especially in densely populated urban areas, could be argued to be a relevant spending priority for a local or city government. The EU's Clean Vehicles Directive sets public procurement targets for LDVs, trucks and buses (EC, 2019a). India's Energy Efficiency Services Limited (EESL) is also undertaking bulk procurement of EVs for government vehicle fleets (IEA, 2020c).

Taxis. Other vehicle fleets may be significant in different contexts. The Netherlands aims for half of its taxi fleet to be ZEVs by 2025, and Chile has a taxi renewal program, that provides access to financing to help taxi drivers acquire electric and hybrid vehicles (IEA, 2020c).

Two- and three-wheelers. In many parts of Asia and in emerging economies two- and three-wheelers make up significant parts of the overall transport stock, and many African countries have growth rates of motorcycles that are amongst the highest in the world (UN Environment, 2020). Electric two- and three-wheelers have important health co-benefits in large cities where such vehicles are in large numbers for personal transportation, or as auto-rickshaws found throughout India and in other Asian countries. The global number of electric two- or three-wheelers currently in use is estimated by the IEA at 350 million, or around 25% of the total stock of these vehicle types - vastly exceeding the current number of electric cars. The majority of two- and three-wheelers are found in China, where many cities have banned ICE two-wheelers (IEA, 2020c).

Light duty commercial vehicles (LCVs) such as vans tend to have a higher mileage than cars, and yet - particularly for local delivery roles – lower range requirements (and for fleets, usually convenient charging points). The high mileage maximizes the value of fuel cost savings once electrified; the other features limit the battery size required, and hence costs. Moreover, the COVID-19 response has increased the use of localized delivery associated with online purchases. This could form a major



growth area for electric vehicles as identified in ITF (2020). Some major retailers and distribution companies are committing to using zero-emission vehicles, including IKEA with a 2025 deadline, complementing zero-emission zones in several European and Chinese cities targeted at freight (C40 Cities, 2020).

Heavy duty trucks can be highly polluting, but their higher power (and often range) demands create challenges with energy storage and the need for fast charging. The best technology path for trucks remains uncertain, and is beyond the scope of this study, but it could emerge as a natural extension of electrification of some of the above modes. Germany has set a goal of electrifying one third of its truck fleet by 2030. Pakistan targets 30% of new truck sales in 2030 to electric vehicles, rising to 90% in 2040, supported by low electricity tariffs for EV charging stations and reduced sales tax for EV trucks. California and seven other states are investigating ZEV mandates for trucks. In the Netherlands the 30-40 largest municipalities are to develop zero-emissions zones for freight vehicles, and long haul freight is required to improve its CO_2 intensity by 30%, by 2030 (IEA, 2020c).

CONCLUSION

For a full century, the transport sector has been marked by an inexorable rise in demand, increasingly dependent upon a single energy source – oil – and for land transport, a single technology – the internal combustion engine. The macro indicators of transport and energy demand and CO_2 emissions still point in the same direction, and improvements in energy and carbon intensity have, if anything, slowed. The trends are unsustainable, for multiple reasons.

However, change is afoot and gathering pace, most obviously for the largest segment of land passenger transport. A new technology wave, of electric vehicles, is emerging. Coupled with a decarbonizing power sector, this can help to deliver deep decarbonization of land transport. Norway more than any other has demonstrated what is possible – investing its oil revenues to secure a modern, clean transport system with over 50% of its car sales being electric, primarily by making EVs more attractive to consumers than ICE vehicles.

As articulated by Sharpe and Lenton (2021), the policies pursued to achieve this, and policy expansion across other regions, have brought EV technology through one 'tipping point' – connecting consumer demand with industry delivering robust, high-performing technology, which is increasingly competitive in terms of overall cost of ownership. As they note, EVs are approaching another tipping point: "as EVs become ever cheaper, consumers will increasingly prefer to buy them, manufacturers will prefer to make them, investors will be more willing to invest, and even governments that care nothing for climate change will want to support the transition". This market tipping point could be reached by 2024, by when a recent report projects that EVs "will have surpassed petrol and diesel cars in almost every car buyer purchase criterion: equal on upfront cost and range, a fraction of the cost to run and maintain, and better acceleration" (Systemiq, 2020).

EV sales globally have grown at an average of over 40%/yr since 2015, and the share of stock, at 46%/yr (with charging points growing at over 80%/yr). Our report has applied established S-curve dynamics to illustrate that the global trends, if sustained, could revolutionize passenger transport within 10-15 years. This could bring the passenger transport transition within striking distance of its essential contribution to the goals of the Paris Agreement.

We have also however underlined that both the pace, and ultimate depth, of the global transition still hinges upon policy, as EV technology, and new business models, have to compete with established infrastructures and powerful interests. As analysed in section 4 and synthesized in our Summary, policy actions are required in three main areas:

- infrastructure (notably, public charging) and integration with the electricity system;
- the alignment of costs and benefits to consumers to ameliorate the barrier of up-front capital costs; and
- fostering and coordinating accelerated but balanced growth of both demand (e.g. through phase-out or stretching performance targets) and supply (by supporting roles in key parts of EV manufacturing supply chains).

Our policy conclusions align well with the recent findings of the global industry initiative EV100 (2021). And as EV100 note, the focus on smaller vehicles goes way beyond private cars to embrace many commercial uses, and is already starting to see technology spillovers into some of the 'harder to treat' arenas of heavier duty vehicles. Overall, EVs intersect with manufacturing, roads and urban planning, charging infrastructure and power system operation – so the success and speed of the transition will be affected by the degree of coordination.

From the global and climate change perspectives however, initiatives which concentrate only on leading countries, companies and technologies will not be enough. Managing transport demand remains an important objective to pursue in tandem, helping to curtail near-term CO_2 emissions and reduce the pressure on future electricity supply systems, and on supply of critical minerals. The slowing trend of global vehicle efficiency is also a warning not only that the conventional technology may be approaching limits, but that older cars which no longer meet new standards – and the factories producing them – often move on to developing countries, exacerbating for example the toll of urban air pollution.

Many developing countries have successfully skipped the age of landline phones to embrace mobile technology – which itself can facilitate smarter transport systems, as suggested in Kenya (Al-Guthmy and Yan, 2020). Whether developing regions can and will 'leap-frog' to more sustainable transport systems, and whether global transport cooperation can deliver a transition on the pace and scale required to meet developmental goals including those of the Paris Agreement, remain the big and urgent policy challenges ahead.

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APPENDIX I: DEPLOYMENT INDICATORS BY COUNTRY

Figure 17 shows the growth of electric car stock by country. From almost nothing in 2010, by 2019 there were over 7 million EVs on the road, but deployment is very varied, with about half in China, followed by the US. The fact that China and the US lead the world in absolute deployment both of vehicles and of public charging infrastructure is of course strongly affected by the size of these countries and their overall car markets. An important complementary picture is given by considering the deployment of electric cars as a share of the overall car market in any given country, and the number of public charging points in relation to the size of the country and number of EVs.

ELECTRIC CAR STOCK BY COUNTRY

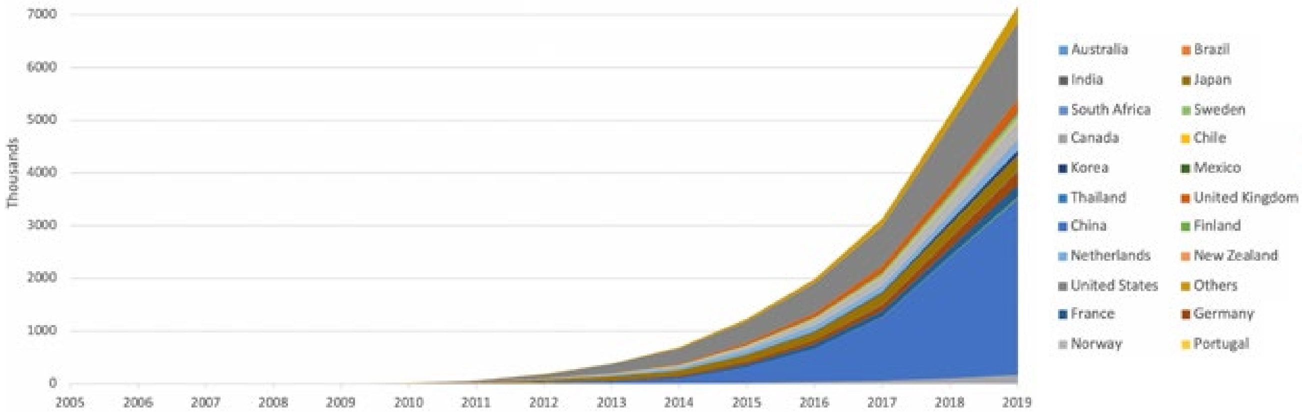

Figure 17: Electric car stock, by country. Source: IEA (2020c), Statistical annex

The leading country for electric cars by market share is Norway, where EVs account for 56% of the total car stock, followed by the Netherlands and Sweden - both of which have shares exceeding 10% (Figure 18. These gives contrasting pictures of the relationship between EV deployment and the density of charging infrastructure. The Netherlands is the country with the third largest number, in absolute terms, of publicly accessible chargers in the world, after China and the US. Given its small size, it has by far the highest density of publicly accessible chargers relative to land area, at about 150 chargers per 100 km$_2$ (Figure 19).

EV SHARE OF PASSENGER CARS

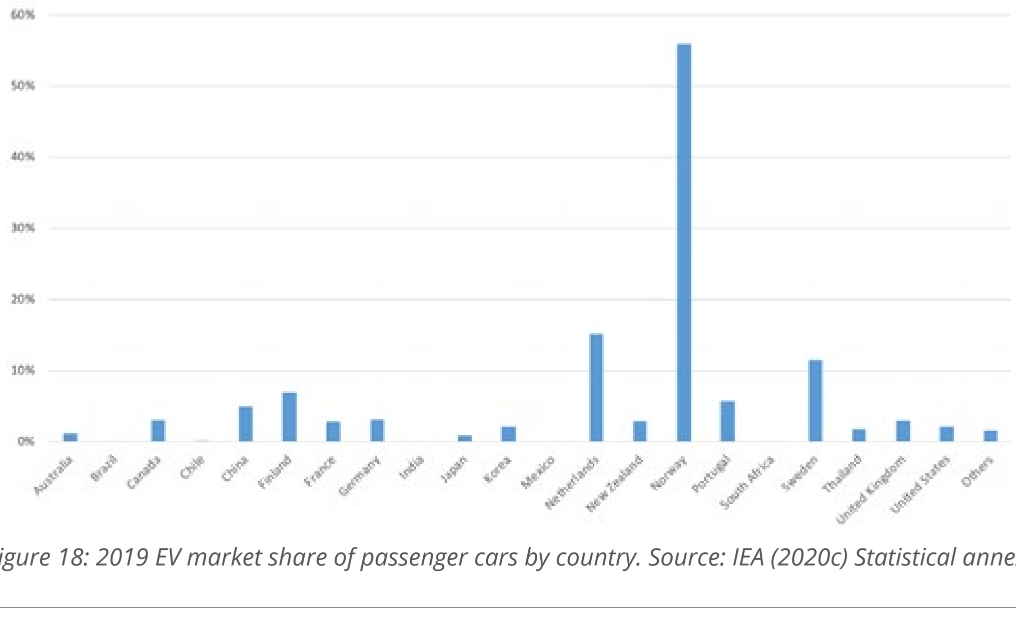

Figure 18: 2019 EV market share of passenger cars by country. Source: IEA (2020c) Statistical annex

PUBLICALLY ACCESSIBLE CHARGERS PER 100 KM$_2$

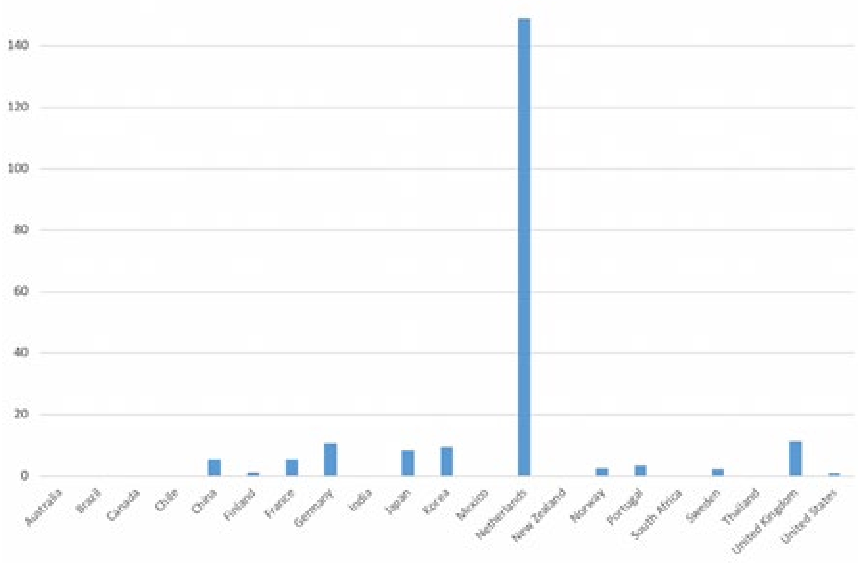

Figure 19: 2019 publicly accessible chargers per 100 km$_2$ by country. Data for number of publicly accessible chargers from IEA (2020c) statistical annex. Countries' land area in square kilometers from World Bank (2020)

PUBLICALLY ACCESSIBLE CHARGERS PER EV IN CIRCULATION

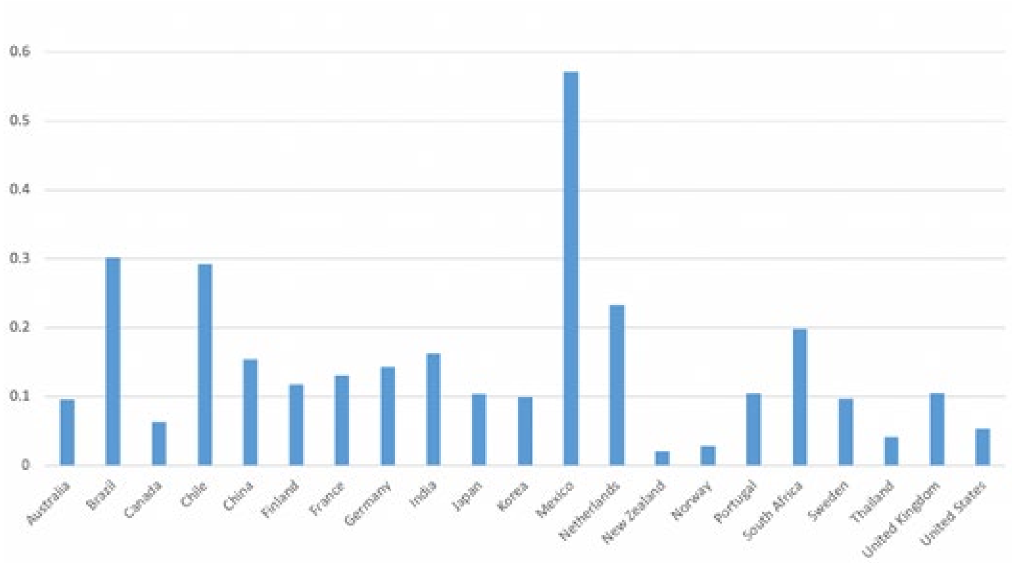

Figure 20: Publicly accessible chargers per electric vehicle in circulation by country. Numbers of EVs and chargers from IEA (2020c) statistical annex.

This density clearly may be an important supporting factor for its high market share of electric cars. The other two countries with more than 10% EVs by 2019, Norway and Sweden, have much lower density of chargers (reflecting much lower population density), at 2.6 and 2.3 chargers per 100 km$_2$ respectively.

Figure 20 shows the density of public EV chargers in relation to the number of EVs. One benchmark is that of 0.10 chargers per EV – one publicly available charger for every ten EVs – as recommended in the EU's Alternative Fuels Infrastructure Directive (IEA, 2020c). Interestingly, whilst some countries have much higher levels – led by Latin American countries, and presumably reflecting EV sales lagging charging infrastructure - Norway's density public charging point density is much lower (one public charger for every 35 EVs). This reflects the wealth and space in a country like Norway, where 58% of respondents reported being able to park on their own property, and 24% had a reserved parking space connected to their dwelling (Christiansen et al., 2017).

APPENDIX II: BENCHMARKS AND S-CURVE METHODOLOGY

OUR APPROACH TO SETTING BENCHMARKS

This report constructs S-curves aiming towards 'Paris-Consistent' future benchmarks. A 'Paris-Consistent' benchmark or scenario is one that is consistent with the central pledge of the Paris Agreement, namely 'holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C' (UN, 2015).

The benchmarks used in this report are derived from five sources, as listed in Box 2, Section 1.4. The Climate Action Tracker (New Climate Institute and Climate Analytics, 2020) and Climate Ambition Benchmarks (Climate Works Foundation et al., 2019) reports provide benchmarks on shares of EVs and CO_2 intensity, based on their authors' analysis of scenarios judged to be consistent with the goals of the Paris Agreement. We also use the central 1.5°C scenario from the UCL Times Integrated Assessment Model (UCL TIAM) to identify additional CO_2 and CO_2-intensity related benchmarks.

CO_2 and CO_2-intensity related benchmarks are also derived from analysis of the database of scenarios reported by Huppmann et al. (2018). The International Institute for Applied Systems Analysis (IIASA) has in recent years established a database of global energy-CO_2 scenarios – the Scenario Explorer database (Huppmann et al., 2018). These include numerous scenarios developed in the context of the IPCC's report on Global Warming of 1.5°C (IPCC, 2018), which assumed a remaining emissions budget of about 580 $GtCO_2$ (median) from 2018 onward, declining to net-zero global emissions by about mid-century (Rogelj et al., (2018) p. 105 and Table 2.2). The scenarios are produced by a range of Integrated Assessment Models (IAMs) which provide a representation of global economic, energy, land use, and climate systems, and enable exploration of the impact of different technological shifts and societal changes on emissions.

The Scenario Explorer database (Huppmann et al., 2018) was used to identify scenarios consistent with climate change of 1.5°C or below. The categories "1.5°C low overshoot" (n=44) and "Below 1.5C" (n=9) were selected. "Low overshoot" scenarios are those "limiting median warming to below 1.5°C in 2100 and with a 50–67% probability of temporarily overshooting that level earlier" (Rogelj et al. (2018) p.100, Table 2.1). "Below 1.5C" scenarios have 50–66% likelihood of keeping peak warming below 1.5°C for the entire 21st century (Rogelj et al. (2018) p.100, Table 2.1). Huppmann et al. also present a category called "1.5C high overshoot" (n=37) scenarios. In these scenarios the probability of temporarily overshooting 1.5°C is greater than 67%. In general, the greater the risk of overshoot, the greater the need for "negative emissions."

In Chapter 2 of the IPCC 1.5 Special Report, the term "1.5°C-consistent pathways" includes scenarios from all three (1.5C low overshoot, Below 1.5, and 1.5C high overshoot) categories (Rogelj et al. (2018) p. 100, Table 2.1). However, the Summary for Policy Makers of the IPCC 1.5 report (IPCC, 2018) focusses on pathways with "no or limited overshoot" – i.e., "below 1.5" and "low overshoot" categories.

As noted, in this report we select scenarios as "Paris-consistent" that we judge to be consistent with the goal of the Paris Agreement of "holding the increase in the global average temperature to well below 2°C above pre-industrial levels and pursuing efforts to limit the temperature increase to 1.5°C above pre-industrial levels" (UN, 2015). We judge that scenarios falling within the categories of "Below 1.5°C" and "1.5°C low overshoot" are "Paris-consistent," and therefore relevant for the purposes of this report. We do not include the category of "1.5°C high overshoot" scenarios within our set of "Paris-consistent" scenarios.

Benchmarks that are derived from the Huppmann et al. database are based on the median values of these "Paris-consistent" scenarios, for each indicator.
Finally, the EV share of sales indicator is supplemented by a 2030 benchmark based on the Net-Zero Emissions by 2050 (NZE2050) scenario from the IEA's World Energy Outlook (2020e).

S-CURVE METHODOLOGY AND TERMINOLOGY

The essential features of growth and diffusion dynamics, particularly those that typify substitution of old technologies by new, start with a period of almost exponential growth, slowing towards linear and then approaching saturation levels. This is most succinctly represented by a logistic (otherwise known as Sigmoid or sometimes Substitution) function. The origins are sometimes traced to ecological population dynamics modelling. In its simplest form, this can be written as Deployment at time t, D(t):

$$D(t) = \frac{K}{1 + \left(\frac{1}{y} - 1\right) e^{-\alpha t}}$$

Where:

K = the final, 'culmination' level of penetration, in units appropriate to the technology

y = initial value as a fraction of the final culmination level

α = intrinsic growth rate (%/yr)

This is essentially the same equation as presented in our first report, *Shape and Pace of Change in Electricity*, but we have amended the notation to reflect as far as possible common terminology in the relevant literature, whilst minimising potential confusion with terminology in mainstream economics. Note also compared to our earlier form, $y = Y_0/K$, hence our previous form $((K - Y_0) / Y_0) = (^1/_y - 1)$.

Starting point. In this approach, at our starting point (implicitly defined as t=0), y is the % in that year of the culmination value. As indicated, in this report, we take the culmination as being 100% EVs, and the starting point as 2015, when electric vehicles were under 1% of global sales (and miniscule in terms of % vehicles on the road). Were actual growth to follow exactly the logistics function at all points, the choice of starting point would not matter. In practice, before 2015, sales were too small and unstable to provide a reliable indication of the potential emergence growth rate and timing.

Initial growth is exponential at rate α, to which observed emergence growth approximates. Note that in the early stages, y is very small, hence $(1/y) >> 1$; and relative to the overall transition process, $t < 1/\alpha$ so that the term $e^{-\alpha t} / y$ dominates in the denominator of the above equation. In the early stages, the equation therefore approximates as:

$$D(t) = \frac{K}{1+\left(\frac{1}{y}-1\right)e^{-\alpha t}} \approx \frac{K}{\left(\frac{e^{-\alpha t}}{y}\right)} = yKe^{\alpha t}$$

So when in the initial phase, ie. when *y* and *t* are sufficiently small, growth is approximately exponential at rate α. Our charts show the implications of a few different intrinsic rates α. Since EVs sales were still only at 3.5% by 2019, the observed emergence rate is almost equivalent to (only slightly lower than) the mathematical intrinsic rate α for the logistics function.

Supplementary note. For those interested in diffusion dynamics, note that a slightly more generalized form of logistics curve replaces t by $(t - t_0)$, where t_0 is any reference date. Some treatments – used to study past transitions - then specify the logistics curve in terms of the mid-point, t_0 then being the date at which diffusion reaches 50% of the culmination value. In this case of course, $y = 0.5$, and the equation becomes simply

$$D(t) = \frac{K}{1 + e^{-\alpha(t - t_0)}}$$

This obviously confirms that in this treatment, at the time $t = t_0$, the diffusion D(t) is K/(1+1) = 50% of the final value; it also shows that the logistics function is symmetric about this mid-point, with earlier points making the exponent positive as $(t - t_0)$ is then negative. However, for forward extrapolations based on observations of initial emergence, as required in our research, obviously it is not helpful to have to specify in advance a mid-point, and confusing to refer to negative time values relative to some future t_0.