The Internal Combustion Engine Bubble

Current auto industry planning is not aligned with a 1.5°C compatible carbon budget and might result in millions of vehicles manufacturers can't sell

The Internal Combustion Engine Bubble

Current auto industry planning is not aligned with a 1.5°C compatible carbon budget and might result in millions of vehicles manufacturers can’t sell

By

Associate Prof. Dr. Sven Teske
Institute for Sustainable Futures, University of Technology Sydney (UTS),
235 Jones Street, Sydney, NSW 2007, Australia

Prof. Dr. Stefan Bratzel, Ralf Tellermann
Center of Automotive Management, University of Applied Sciences (FHDW) Bergisch Gladbach
An der Gohrsmühle 25, 51465 Bergisch Gladbach, Germany

Dr. Benjamin Stephan, Dr. Mauricio Vargas
Greenpeace Germany,
Hongkongstraße 10, 20457 Hamburg, Germany

Published by Greenpeace e.V., Hongkongstr. 10, 20457 Hamburg, Phone +49 40 3 06 18-0, www.greenpeace.de **Press Office** Phone +49 40 3 06 18-340, presse@greenpeace.de **Political Unit in Berlin** Marienstraße 19 – 20, 10117 Berlin, Phone +49 30 30 88 99 - 0 **Responsible for content** Benjamin Stephan **Cover photo** Parked cars near Bremerhaven, Germany © Greenpeace Published November 2022 S03881

Executive Summary

The internal combustion engine (ICE) needs to be phased out, and the vehicle fleet needs to be electrified to make road transport compatible with the Paris Agreement's goal of limiting warming to 1.5°C. However, just how fast this transition must happen, what it means for the auto industry and whether the companies' planning delivers what is needed to comply with the 1.5°C goal remains unclear. This report aims to shed light on these questions. It defines the number of ICE vehicles that could still be sold within a 1.5°C carbon trajectory and projects the auto industry's ICE sales based on the assessment of four major manufacturers' plans – Toyota, Volkswagen, Hyundai / Kia and General Motors – and quantifies the overshoot.

To do so, this report draws on the concept of the "carbon bubble" – fossil fuel reserves in the books of energy companies that need to remain in the ground if we are not to exceed 1.5°C of warming.[1] These unburnable reserves result in stranded assets and pose significant other financial risks for companies and their investors. This study applies the bubble concept and examines the extent to which these risks exist in the transport sector.

The body of this report consists of three key chapters: Chapter 2 lays out how many light-duty vehicles (LDV) – cars and vans – with internal combustion engines can still be sold worldwide before the global CO_2 budget for limiting a temperature increase to a maximum of 1.5˚C is exhausted. Current and future trajectories for car sales are broken down into five drive-train technologies with four different engine sizes. The aim of this analysis is not to forecast the possible market development of the global LDV market but to develop a 1.5°C-compliant benchmark for sales trends in the auto sector. The analysis concludes in a quantified amount of ICE vehicles which can be sold before the manufacturing of internal combustion engines needs to cease globally. Chapter 3 projects future ICE sales of Toyota, Volkswagen, Hyundai/Kia and General Motors based on the companies' announced sales targets for electric vehicles. Chapter 4 identifies the gap between the manufacturers' projected future sales and the number of ICE vehicle sales compatible with a 1.5°C carbon trajectory. As governments are expected to increase legislative and regulatory efforts to comply with the 1.5°C target of the Paris Agreement, this gap – an ICE bubble – is expected to become an increasing business and financial risk.

1 UBA (2021), Carbon Bubble – Analyses, economic risks, measures and instruments, Berlin. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2021-07-06_texte_23-2021_carbon_bubble_eng.pdf
Carbon Tracker (2022), Carbon Bubble https://carbontracker.org/resources/terms-list/

Key findings

- A carbon budget of 53 Gt has been identified for light-duty vehicles based on a global carbon budget of 400 Gt between 2020 and 2050, which would allow warming to be limited to 1.5°C with a likelihood of 67%.

- Current car manufacturer planning is projected to create an ICE bubble of at least 330 to 463 million LDVs – vehicles the industry plans to sell and that exceed the number of possible sales under a 1.5°C-compatible carbon budget.
  Without significant changes in the structure of the LDV market (vehicle size, horsepower) and use patterns (vehicle life, mileage), the carbon budget of 53 Gt allows for the sale of an additional 315 million ICE vehicles as of 2022. At the same time, however, projected ICE sales range between at least 645 million and 778 million vehicles. This represents an overshoot of 105% to 147%% compared to the 1.5°C -compatible number of ICE sales.
  These projections have been extrapolated for the entire industry based on a detailed analysis of BEV sales targets and ICE phase-out announcements of four leading auto manufacturers: Volkswagen, Toyota, Hyundai / Kia and General Motors (GM).

- To decarbonize road transport by 2050, and considering the limited number of ICE vehicles that can still be sold, automakers need to phase out the production of ICE LDVs by 2030. Total decarbonization of the existing LDV fleet will take an additional 20 years due to the remaining lifespan of ICE vehicles sold until 2030.

- The calculated ICE phase-out trajectory following the projected ICE sales based on current planning would lead to cumulative carbon emissions (2020 to 2050) amounting to a minimum of 98 $GtCO_2$ and a maximum of 116 $GtCO_2$. These overshoot emissions of at least 45 $GtCO_2$ are in the order of the cumulative carbon budget of the global buildings sector and, therefore, very unlikely to be compensated by other sectors.

- Neither Volkswagen, Toyota, Hyundai / Kia, nor General Motors are on a 1.5°C-compatible trajectory. Their projected ICE vehicle sales all exceed the maximum permitted within the 1.5°C carbon budget. The last to announce a transition to BEVs, Toyota is performing the worst among the companies analyzed with projected sales that exceed the 1.5°C-compatible volume by 55 to 71 million vehicles or 144% to 184%. Among the companies analyzed, Volkswagen had the highest volume of BEV sales in 2021 and hence the best starting point. The manufacturer is projected to exceed 1.5°C-compatible ICE sales by 37 to 50 million vehicles or 100% to 136% as its speed of transition is comparatively slow. Hyundai/Kia's projected sales exceed the 1.5°C-compatible volume by 35 to 44 million or 124% to 159%. Even GM, the company with the most ambitious electrical vehicle transition process, which aims to phase out the internal combustion engine by 2035, is projected to exceed the number of ICE sales compatible with the 1.5°C carbon budget by 6 to 21 million vehicles or 25% to 90%.

- The lack of speed in transitioning from ICE to electric drivetrains is the main cause for the potential emergence of an ICE bubble. Phasing out the internal combustion engine and fully electrifying LDV sales is necessary by 2030 to stay within a 1.5°C carbon budget. However, the industry's plans – at least the plans of traditional manufacturers such as Volkswagen, Toyota, Hyundai/Kia, and GM – lead to projections of only 52% of battery electric vehicle sales by 2030. This poses a significant business risk to these manufacturers as they risk losing market share to new all-electric market entrants ready to fill the gap.

- The ICE bubble, resulting in stranded assets and potential financial problems for auto manufacturers, poses considerable risks to financial markets. With over US$1.2 trillion in outstanding debt and a market capitalization of US$859 billion among the twelve largest auto manufacturers alone, over US$2 trillion are at risk globally – even more if automotive suppliers are also considered.

Figure I:
Global ICE sales projections vs remaining 1,5°C compatible number of ICE sales

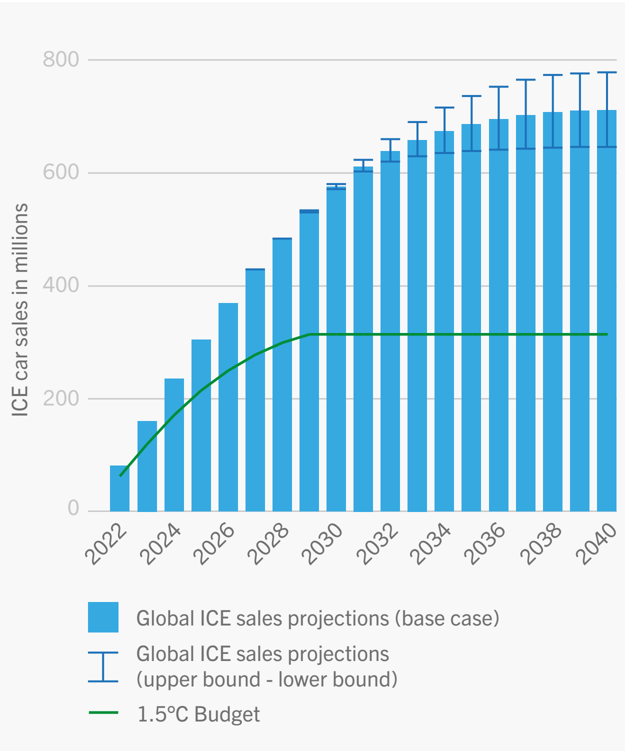
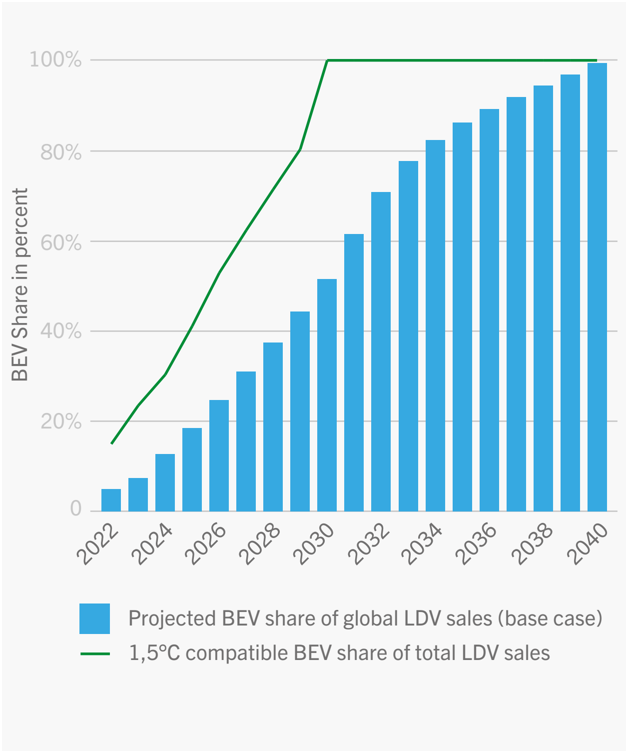


Figure II:
BEV share of total LDV sales



Protest at a meeting of EU Transport Ministers in Luxembourg 2019.

1. Introduction

The internal combustion engine (ICE) needs to be phased out, and the vehicle fleet needs to be electrified to make road transport 1.5°C compatible. However, just how fast this transition must happen, what it means for the auto industry and whether the companies' planning delivers what is needed to comply with the 1.5°C goal remains unclear. This report aims to shed light on these questions. It defines the number of ICE vehicles that could still be sold within a 1.5°C pathway, projects the auto industry's ICE sales based on the assessment of four of the major manufacturers' plans – Toyota, Volkswagen, Hyundai/Kia and General Motors – and quantifies the overshoot.

To do so, this report draws on the concept of the "carbon bubble" – fossil fuel reserves in the books of energy companies that need to remain in the ground if we are not to exceed 1.5°C of warming.[2] These unburnable reserves result in stranded assets and pose significant other financial risks for companies and their investors. This study applies the bubble concept and examines the extent to which these risks also exist in the transport sector.

The body of this report consists of three key chapters: Chapter 2 lays out how many light-duty vehicles (LDV) – cars and vans – with internal combustion engines can still be sold worldwide before the global CO_2 budget for limiting a temperature increase to a maximum of 1.5˚C is exhausted. Current and future trajectories for LDV sales are broken down into five drive-train technologies with four different engine sizes. The aim is not to forecast the possible market development of the global passenger vehicle market but to develop a 1.5°C-compliant benchmark for sales trends in the auto sector. The analysis concludes in a quantified amount of ICE vehicles which can be sold before the manufacturing of internal combustion engines needs to cease globally. Chapter 3 projects ICE sales of Toyota, Volkswagen, Hyundai/Kia and General Motors based on the companies' announced sales targets for electric vehicles. Chapter 4 identifies the gap between the manufacturers' projected future sales and the number of ICE vehicle sales compatible with a 1.5°C carbon trajectory. As governments are expected to increase legislative and regulatory efforts to comply with the 1.5°C target of the Paris Agreement, this gap – an ICE bubble – is expected to become increasing business and financial risk.
The Institute for Sustainable Futures, University of Technology Sydney (UTS/ISF) and the Center of Automotive Management (CAM), University of Applied Sciences (FHDW) in Bergisch Gladbach have been commissioned by Greenpeace Germany to carry out this research.

2 UBA (2021), Carbon Bubble – Analyses, economic risks, measures and instruments, Berlin. https://www.umweltbundesamt.de/sites/default/files/medien/1410/publikationen/2021-07-06_texte_23-2021_carbon_bubble_eng.pdf
Carbon Tracker (2022), Carbon Bubble https://carbontracker.org/resources/terms-list/

2. Determining the remaining global market volume for internal combustion engines (ICE) for light-duty vehicles under a 1.5˚C carbon budget trajectory

The Paris Climate Agreement (UNFCCC, 2015) "notes that (...) emission reduction efforts will be required (...) to hold the increase in the global average temperature to below 2°C above pre-industrial levels and to pursue efforts to limit the temperature increase to 1.5°C above pre-industrial levels (...)." The Intergovernmental Panel on Climate Change (IPCC) further quantified the carbon budget to achieve this target in its Sixth Assessment Report of the Working Group (IPCC, 2021). According to the IPCC, going forward until 2050, the global carbon budget to limit global warming to 1.5°C with a 67% likelihood is 400 $GtCO_2$.

This analysis compares a global carbon budget for light-duty vehicles (LDV) with internal combustion engines (ICE) of around 50 to 55 $GtCO_2$ (Teske et al., 2022)[3] with the published plans of four leading auto manufacturers. The remaining global carbon budget for LDV is based on the One Earth Climate Model (OECM) – a global 1.5˚C pathway for all industry sectors and the energy industry overall. The One Earth Climate Model (OECM) is an integrated assessment model for climate and energy pathways, focusing on 1.5°C scenarios (Teske et al., 2022). This study focuses on current and future trajectories for light vehicle sales broken down into five drive-train technologies with four different engine sizes.

2.1 The global light-duty vehicle market

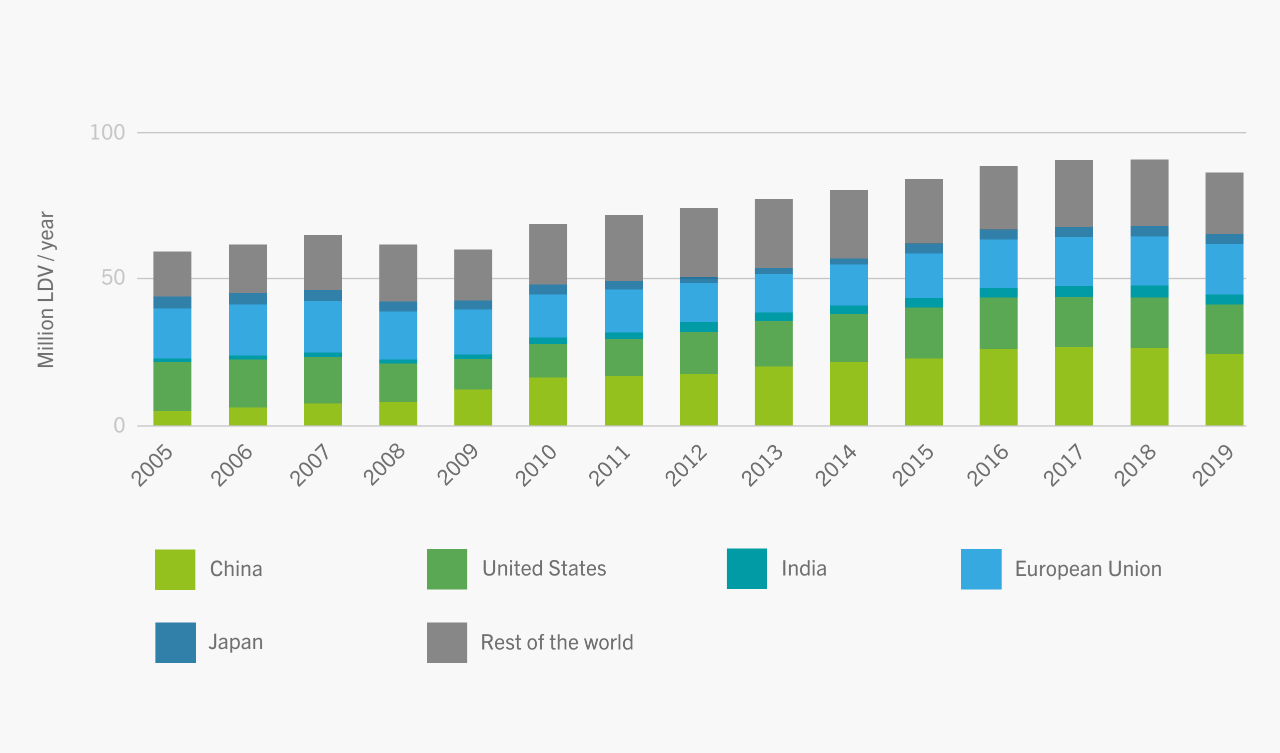
The global light vehicle market has grown 2.8% per year on average since 2005. Only during the global financial crises in 2008 and 2009 and the beginning of the COVID-19 pandemic did the market decrease by around 5%. However, in both cases, sales jumped back the following year. In other words, the market did not actually experience a decline, customers simply postponed buying cars. Annual regional markets for LDV in the United States and the European Union have been relatively constant since 2005. They have seen the same sales volume of around 15.5 million units per year (OICA, 2021).[4] The Japanese market has experienced a slight downward trend, from 4.3 million sales in 2005 to 3.5 million per year since 2015. The strongest growth has been in China, where annual LDV sales grew fivefold from 2005 – from 5 million to 25 million in 2019 (Figure 1).

---

3 Teske et al. (2022); Teske, S., Pregger, T. (2022). OECM 1.5°C Pathway for the Global Energy Supply. In: Teske, S. (eds) Achieving the Paris Climate Agreement Goals. Springer, Cham. https://doi.org/10.1007/978-3-030-99177-7_12

4 OICA (2021); International Organization of Motor Vehicles Manufacturers, website, online database, downloaded in September 2021, https://www.oica.net/category/sales-statistics/

Figure 1:
Light duty vehicle sales by region 2005 to 2019[5]



The global LDV market is dominated by vehicles with internal combustion engines. Table 1 shows that about 99% of all new vehicles sold in 2019 had ICE drive trains, and only 0.5% were electric vehicles. The market share for battery electric vehicles increased significantly to just below 6% in 2021 (BNEF, 2021).[6] The dominant LDV engine power class in 2019 and 2020 was between 101 kW and 200 kW (45%) followed by 50 kW to 100 kW (31%). The market segmentation according to power classes is based on 2019 market data – the most recent available at the start of this project. However, the results have been complemented with 2020/2021 data on market volume and market distribution of drive-trains to account for the rapid increase in BEV sales during this period.

5 Source: IEA 2021

6 BNEF (2021), Global EV Sales on Track to Hit Record 6.3 Million in 2021: BNEF

Table 1:
Global LDV market by drive-train technology 2019 and market shares of four auto manufacturers[7]

Engine Type	Tag	Power Class	Marketshare by engine – based on the four companies	Sum four companies	Volkswagen VW, Audi, Skoda, Seat, Porsche	Toyota Toyota, Lexus	Hyundai/Kia Hyundai, Kia, Genesis	GM Chevrolet, GMC, Cadillac, Buick
Petrol (incl. HEV)	petrol	less 50 kW	1.81%	655,650	242,298	0	413,353	0
	petrol	50-100 kW	30.87%	11,199,040	3,455,748	3,444,723	2,708,519	1,590,050
	petrol	101-200 kW	44.39%	16,105,016	4,354,147	4,621,844	2,930,581	4,198,444
	petrol	above 200 kW	14.38%	5,214,945	812,926	2,439,915	187,478	1,774,625
Diesel	diesel	below 50 kW	0.00%	1	0	0	1	0
	diesel	50-100 kW	4.04%	1,465,217	674,954	4,682	785,581	0
	diesel	101-200 kW	3.27%	1,187,144	975,351	14,851	189,522	7,420
	diesel	above 200 kW	0.53%	192,661	69,878	0	1	122,782
PHEV (petrol/diesel)	PHEV	below 50 kW	0.00%	148	0	0	148	0
	PHEV	50-100 kW	0.09%	32,188	425	18,210	13,541	12
	PHEV	101-200 kW	0.09%	33,476	8,809	2,138	17,614	4,915
	PHEV	above 200 kW	0.03%	11,152	11,127	0	0	25
BEV	BEV	below 50 kW	0.05%	18,480	161	0	18,319	0
	BEV	50-100 kW	0.11%	38,656	29,514	0	5,800	3,342
	BEV	101-200 kW	0.13%	48,481	13,509	3,055	15,604	16,313
	BEV	above 200 kW	0.02%	8,065	8,065	0	0	0
Fuel Cell	FCEV	below 50 kW	0.00%	24	0	0	24	0
	FCEV	50-100 kW	0.00%	0	0	0	0	0
	FCEV	101-200 kW	0.01%	1,994	0	1,702	292	0
	FCEV	above 200 kW	0.00%	0	0	0	0	0
Other (lpg, cng, ethanol, …)	other	below 50 kW	0.01%	3,286	34	0	3,252	0
	other	50-100 kW	0.17%	60,833	55,938	0	4,895	0
	other	101-200 kW	0.00%	1,121	1,117	0	4	0
	other	above 200 kW	0.00%	1	0	0	0	1
Total internal combustion engines			99.47%	36,277,579	10,714,000	10,551,121	7,294,528	7,717,930
Total			100.00%		Global sales: 86,892,329			

7 Market analysis conducted by the Center of Automotive Management for this report

Banner in front of South Korean carmaker Hyundai Motors HQ calling for the phase-out of internal combustion engines, 2020.
© Sungwoo Lee / Greenpeace

2.2 Carbon budget

The global carbon budget identifies the total amount of energy-related CO_2 emissions available to limit global warming to a maximum of 1.5°C with no/low overshoot. The Intergovernmental Panel on Climate Change (IPCC) is the United Nations body for assessing the science related to climate change. In August 2021, the IPCC published a new report determining that the global carbon budget for the period between 2020 and 2050 to limit temperature increase to 1.5˚C with a 67% probability is 400 $GtCO_2$ (IPCC AR6, 2021).[8]

The UTS One Earth Climate Model (OECM) is an integrated energy assessment model to develop net-zero targets based on science for all major industries in a granularity and with the key performance indicators (KPI) needed to make short-, mid- and long-term investment decisions (Teske et al., 2020).[9] The 1.5˚C emission pathways developed by UTS are no/low overshoot scenarios (SSP 1) as defined by the IPCC: this means that a carbon budget overshoot is avoided and that already released CO_2 is not assumed to be 'removed' by unproven technologies still under development such as carbon capture and storage (CCS). The OECM does consider negative emissions, but only "natural carbon sinks" such as forests, mangroves, and seaweed to compensate process emissions that are currently unavoidable, such as from cement production. The OECM uses this overall remaining carbon budget and develops energy scenarios and emission pathways for all major industries, including the buildings and transport sectors. The model also divides these large sectors into sub-sectors for specific industries.

The OECM remains within an energy-related carbon budget of 400 GtCO2 while the recently released Net Zero scenario of the International Energy Agency (IEA NZE, 2021)[10] leads to "(…) cumulative energy-related and industrial process CO_2 emissions between 2020 and 2050 of 460 $GtCO_2$." In August 2021, the Intergovernmental Panel on Climate Change (IPCC), the United Nations body for assessing the science related to climate change, identified the global carbon budget to limit warming to 1.5˚C with 67% likelihood as 400 $GtCO_2$ and 50% likelihood as 500 $GtCO_2$ between 2020 and 2050 (IPCC AR6, 2021. Another key differentiation between OECM and IEA NZE is that due to the use of technical measures to remove CO_2 after emissions, the IEA NZE classifies therefore as an IPCC SSP2 scenario. Figure 2 shows the shares in percent and Table 2 provides cumulative CO_2 emissions in gigatons for various industries.

8 IPCC (2021), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.). Cambridge University Press.

9 Teske (2020), Teske S, Niklas S, Atherton A, Kelly S, Herring J. Sectoral Pathways to Net Zero Emissions. Sydney, Australia; 2020.

10 IEA (2021), Net-Zero by 2050 – A Roadmap for the Global Energy Sector. Paris, France; 2021.

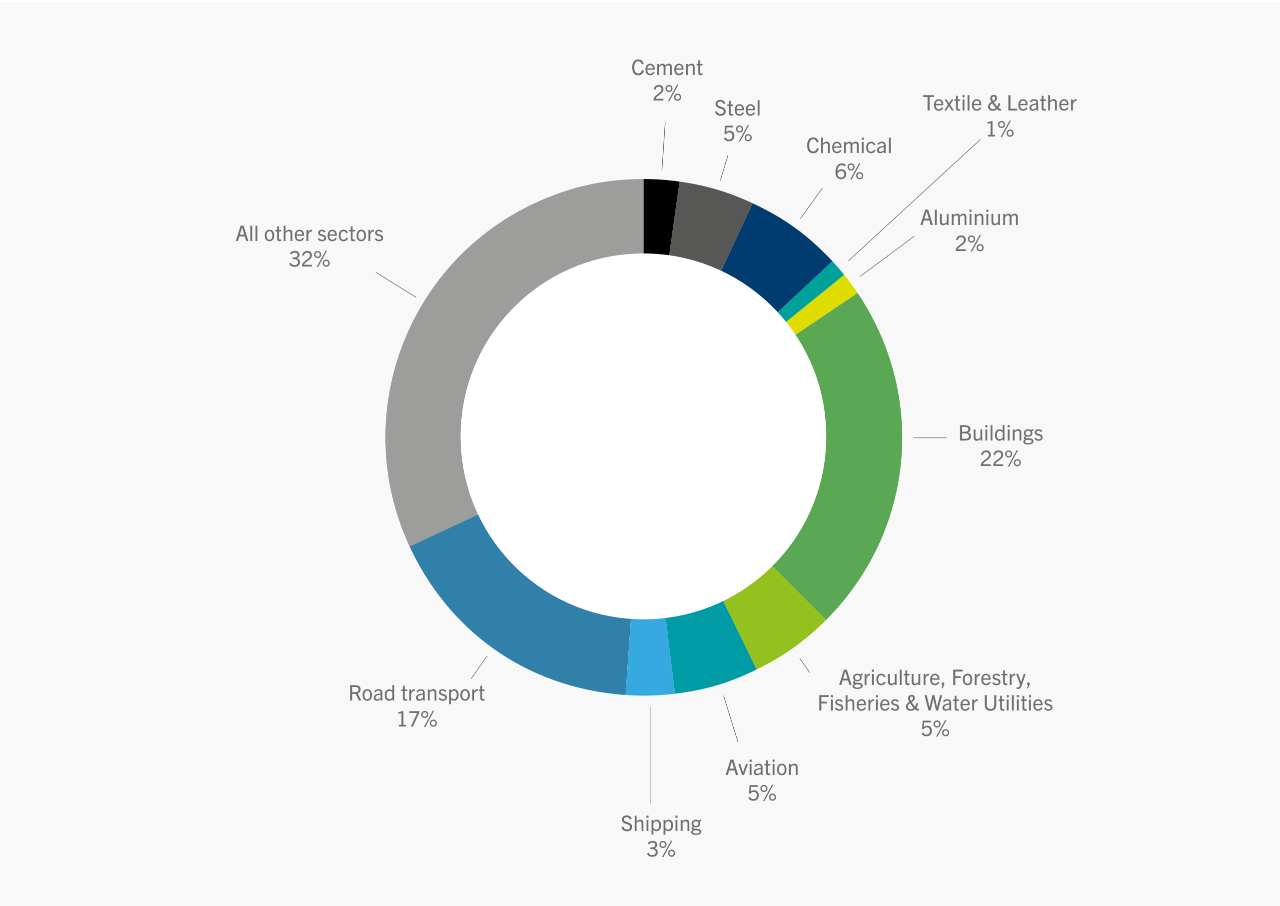
Table 2:
Global carbon budgets – cumulative energy-related CO_2 emissions by industry sectors

Global carbon budget for energy relative CO_2 emissions by subsector (2020-2050) Total 400 $GtCO_2$ – 1.5˚C (67% likelihood)	2020-2030	2020-2050
Cement (process heat, fuels & electricity)	6	9
Steel (process heat, fuels & electricity)	14	19
Chemical industry (process heat, fuels & electricity)	17	25
Textile & leather (process heat, fuels & electricity)	3	4
Aluminium (process heat, fuels & electricity)	5	6
Buildings – commercial, residential incl. construction- (heat, fuels & electricity)	69	88
Fisheries (fuels & electricity)	0	1
Agriculture & food processing (heat, fuels & electricity)	10	14
Forestry & wood (heat, fuels & electricity)	4	5
Water utilities (heat, fuels & electricity)	1	1
Aviation – transport services	15	20
Aviation industry direct (fuels & electricity)	0	0
Navigation – transport services	8	13
Navigation industry direct (fuels & electricity)	0	0
Road transport – transport services	63	80
Road transport industry direct (fuels & electricity)	2	2
Energy industry – production of fossil fuels	**47**	**84**
Remaining energy services (fossil fuels)	4	5
Utilities (power & gas) – distribution	**9**	**15**
Remaining electricity services	1	1
Other conversions & losses	7	9
Total cumulative energy related CO_2 emissions	**285**	**400**

The 1.5˚C carbon budget for LDVs is based on the OECM global scenario results. According to this analysis (Teske et al., 2022), the remaining carbon budget for road transport services between 2020 and 2050 is 68 $GtCO_2$. Itis assumed that 75% of the global carbon budget for road transport can be assigned to LDVs. Based on those assumptions, the remaining carbon budget for LDVs is 51 $GtCO_2$. A more detailed analysis of the global transport industry (road and rail), including freight transport, published in 2021 (Teske et al., 2021b), identified a carbon budget of 30 $GtCO_2$ for the freight industry and 50 $GtCO_2$ for passenger transport.

Therefore, in this analysis, we identified the remaining carbon budget for LDVs not as a fixed number but as a target in the range between 50 $GtCO_2$ and 55$GtCO_2$. That is because calculating specific vehicle numbers with a wide range of engine types and usage habits results in a variation in fuel consumption per vehicle. Thus, the calculated carbon budget includes a degree of uncertainty.

Figure 2:
Global carbon budget — share by industry sector



Chevrolet Silverados and GMC Sierras – GM's most sold models in the US – ready for delivery at the pickup truck plant in Fort Wayne, Indiana, U.S., 2018.

2.3 Methodology

Calculating global CO_2 emissions from new and existing light-duty vehicles requires the following data:

- Specific energy demand per kilometre of the vehicle model in joule per kilometre
- Average annual driven kilometres
- Energy source (petrol, diesel, electricity etc.)
- Emission intensity per unit of energy

Using these parameters, the specific CO_2 emissions per driven kilometre can be calculated for each vehicle model. The total annual CO_2 emissions can then be calculated by multiplying all kilometres driven in a year. Furthermore, the emissions over the whole lifetime of the vehicle need to be considered. To calculate lifetime emissions, vehicle specific emissions per kilometre need to be multiplied by the kilometres driven over the lifetime of the vehicle.

Example: The average new passenger car registered in the European Union emitted 108.2 grams of CO_2 per km in 2020 (ACEA 2021a).[11] The current average vehicle lifespan in Western Europe is 18.1 years (Held 2020).[12] In 2020, the average distance travelled by car and year was assumed to be 15,000 km. This assumption is based on European data which suggest that the average annual mileage is 18,000 km (Marrero et al., 2019)[13] in Western Europe, 20,200 km in the USA (Statista, 2021)[14] and 12,100 km in Australia (ABS, 2020).[15] 5 Based on this data, each new car sold in the European Union emits 24.3t CO_2 over a lifespan of 15 years. A high technical resolution for the calculation method is required to capture the effect of changing vehicle technologies, changes in the type of fuel used, and a transition towards electric drives on total emissions over time – both annually and cumulative. Table 3 provides an overview of the calculation method used for this analysis.

---

11 ACEA (2020), Interactive map – CO2 emissions from new passenger cars in the EU, by country, 18 October 2021, https://www.acea.auto/figure/interactive-map-co2-emissions-from-new-passenger-cars-in-the-eu-by-country/

12 Held (2020), Held, M., Rosat, N., Georges, G. et al. Lifespans of passenger cars in Europe: empirical modelling of fleet turnover dynamics. Eur. Transp. Res. Rev. 13, 9 (2021). https://doi.org/10.1186/s12544-020-00464-0

13 Marrero et al (2019), Marrero, Gustavo & López, Jesús & González, Rosa Marina. (2019). Car usage, CO2 emissions and fuel taxes in Europe. Journal of the Spanish Economic Association. 10.1007/s13209-019-00210-3.

14 Statista (2021), Average annual number of kilometers driven by circulating vehicles in the United States from 2013 to 2020, https://www.statista.com/statistics/1266927/us-average-annual-mileage-of-vehicles-in-use/

15 ABS (2020), Australian Bureau of Statistic, Survey of Motor Vehicle Use, Australia, 21 December 2020, https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release

Table 3:
Overview calculation method

		Calibration with historical data		Projection			
		2005 - 2020	Data source / calculation method	2020 - 2025 near-term	2026 - 2030 mid-term	2031 - 2050 long-term	Data source / calculation method
Market							
Total LDV stock	[1]	Statistics	IEA/Center of Automotive Management	Calculated	Calculated	Calculated	
Annual deviation of total LDV stock	[%/yr]	Calculated	deviation to previous year	Input	Input	Input	
Annual LDV sales	[1]	Statistics	Center of Automotive Management	Input	Input	Input	
Annual retired LDV	[1]	Calculated	annual vehicle stock increase versus annual LDV sales	Calculated	Calculated	Calculated	
Annual retirement share	[%]	Calculated	retirement rated based on vehicle stock	Input	Input	Input	
Technology							
Drive-train market: Annual sales							
ICE - petrol	[1]	Statistics	Center of Automotive Management	Calculated	Calculated	Calculated	
ICE - diesel	[1]	Statistics	Center of Automotive Management	Calculated	Calculated	Calculated	
ICE - other fuels (ethanol, methanol, natural gas, biofuels)	[1]	Statistics	Center of Automotive Management	Calculated	Calculated	Calculated	Calculated with market shares see below
Plug-in hybrid / Hybrid (PHEV)	[1]	Statistics	Center of Automotive Management	Calculated	Calculated	Calculated	
Battery Electric Vehicle (BEV)	[1]	Statistics	Center of Automotive Management	Calculated	Calculated	Calculated	
Fuel Cell / Hydrogen	[1]	Statistics	Center of Automotive Management	Calculated	Calculated	Calculated	
Drive-train market: Shares							
ICE - petrol	[%/yr]	Calculated	calculated share based on	Input	Input	Input	Market share input
ICE - diesel	[%/yr]	Calculated	LDV sales statistics	Input	Input	Input	based on
ICE - other fuels (ethanol, methanol, natural gas, biofuels)	[%/yr]	Calculated		Input	Input	Input	historical market shares
Plug-in hybrid / Hybrid (PHEV)	[%/yr] [1]	Calculated	Market shares calculated	Input	Input	Input	and annual deviation

Battery Electric Vehicle (BEV)	[%/yr]	Calculated	based on total annual LDV sales	Input	Input	Input	with X% increase/ decrease
Fuel Cell / Hydrogen	[%/yr]	Calculated		Input	Input	Input	different growth rates for near/mid/long-term
Engine power							
below 50	[kW]	Calculated	Calculated with actual sales	Input	Input	Input	Market share input based on
50-100	[kW]	Calculated		Input	Input	Input	market shares of previous year
101-200	[kW]	Calculated		Input	Input	Input	and annual deviation with X% increase/-decrease
above 200	[kW]	Calculated		Input	Input	Input	different growth rates for near/mid/long-term
Fuel Efficiency & Emissions							
Internal Combustion Engines (petrol, diesel, hybrids, other fuels)							
Average fuel consumption by technology and engine power	[1/100km]	Statistics	Center of Automotive Management	Input	Input	Input	Fuel consumption of base year x efficiency factor
Fuel emission factors	[kgCO_2/ litre]	Statistics	UBA	Constant			
Average emissions per kilometre	[gCO_2/ km]	Calculated with factors seeabove for each technology and engine power class					
Electric Drives (PHEV, BEV, H2)							
Average electricity consumption by technology and engine power	[kWh/ 100km]	Statistics	Center of Automotive Management	Input	Input	Input	Electricity consumption of base year x efficiency factor
Emission intensity of electricity generation		Electricity generation to supply required electricity either directly to BEV or to produce H2 according to OECM 1.5˚C scenario					
Transport Service							
Total annual passenger kilometre	[million pkm/yr]	Statistics	OECD - International Transport Forum	Calculated	Calculated	Calculated	Passenger kilometre previous year X% increase/ decrease
Annual deviation of total passenger kilometre	[%/yr]	Calculated	deviation to previous year	Input	Input	Input	
Average annual kilometre per passenger car	[km/car year]	Statistics	Center of Automotive Management	Calculated	Calculated	Calculated	
Average passenger per car	[1]	Calculated		Input	Input	Input	Assumed passenger occupancy per car

The LDV market is broken down into six different drivetrain technologies:

1. Internal combustion engine (ICE) petrol
2. Internal combustion engine (ICE) diesel
3. Internal combustion engine (ICE) other fuels, e.g. methanol, ethanol, natural gas, biodiesel
4. Plug-in hybrids and hybrids (PHEV)
5. Battery electric vehicles (BEV)
6. Fuel cell and hydrogen vehicles

Each drivetrain technology is subdivided into four engine power classes:

1. < 50kW
2. 51 kW – 100 kW
3. 101kW -200 kW
4. > 200 kW

Thus, the LDV market is broken down into 24 market segments. Based on historical sales between 2005 and 2020 (IEA 2020b),[16] the market shares are calculated for each segment in regard to the total global annual LDV sales. The calculation method is reversed for the market projection from 2022 until 2050, and the market shares are inputs, while the annual LDV unit numbers are calculation results.

Furthermore, LDV stock increase has been calculated based on the historical development of overall LDV stock (OICA, 2021)[17]and annual LDV sales (OICA, 2021, IEA, 2020b). The delta between annual LDV sales and the actual increase of the LDV stock indicates the number of LDVs retired yearly. Based on this, the average retirement share in percent of total LDV stock has been calculated. Again, the calculation method was reversed, and the number of LDVs retired yearly was calculated using long-term average retirement rates.

The calculated number of LDVs was distributed into the 24 segments according to the average market share of the past 15 years. The total number of vehicles for each of the 24 sectors was calculated – considering sales and retired vehicles – for each year from 2020 to 2050. Furthermore, energy demand, fuel demand and resulting emissions were calculated for each vehicle segment, considering the assumed increase in efficiency over time.

16 IEA (2020b), Global car sales by key markets, 2005-2020, International Energy Agency, online database last updated 17 May 2020, https://www.iea.org/data-and-statistics/charts/global-car-sales-by-key-markets-2005-2020

17 OICA (2021), International Organization of Motor Vehicles Manufacturers, website, online database, downloaded in September 2021, https://www.oica.net/category/sales-statistics/

Finally, the energy demand of all vehicles requiring electricity – either directly, such as BEVs, or to produce hydrogen fuels – was calculated. The calculation of CO_2 emissions from electricity generation is based on the OECM 1.5°C power generation scenario. The OECM scenario decarbonizes electricity generation gradually from around 500g CO_2 per kWh in 2020 to 135g CO_2 per kWh in 2030, achieving complete decarbonization by 2050 (see Annex for additional data).

The phase-out of ICE vehicles via decreased market share – compensated by BEVs – is based on the remaining carbon budget and not on an actual BEV market forecast.

2.4 Assumptions on light-duty vehicle market development

The assumptions for the calculated remaining ICE LDV sales permitted under the Paris Climate Agreement are provided in this section. Table 4 shows assumed global LDV sales until 2050. In 2020, due to the COVID-19 pandemic, global LDV sales dropped to 77.7 million units, 9 million fewer than the previous year. However, in 2021, the market showed signs of recovery, and sales increased by 3.3 million units. In this analysis, we assume that the long-term average market volume will remain the same as it was between 2005 and 2020, with around 75 million vehicles sold yearly. The retirement rate – looking at the total global vehicle stock – was about 5% over the past 15 years. Based on annual sales, we calculated the average historical retirement rate to be roughly 63%. For future projection, we assume that the annual retirement rate will increase to 80%, resulting in a higher replacement rate of old ICE vehicles with more efficient and electric vehicles.

Table 4:
Projection of global annual LDV sales until 2050

Global LDV Market	Unit	2019	2020	2021	2022	2025	2030	2040	2050
Global LDV sales	[million]	86.9	77.7	81.0	75.0	75.0	75.0	75.0	75.0
Retirement rate -based on total vehicle stock	[%/yr]	5%	5%	5%	5%	5%	5%	4%	4%
Retirement rate -based on annual LDV sales	[%/yr]	63%	73%	75%	75%	80%	80%	80%	80%

The assumed market shares by vehicle class are shown in Table 5. Battery-electric vehicles (BEV) are rapidly increasing and will replace ICE as the main market segment by 2025. Furthermore, the market by engine size is projected to remain stable. Smaller city cars with petrol- and diesel-powered engines up to 50 kW will be replaced by BEVs, but the overall market share of small cars will not change. Based on observations of the market over the past years, the assumption is that average car size will not decrease even with electric vehicles.

Table 5: Assumed market share by vehicle class 2019 to 2050

Light-duty vehicles		Unit	2019	2021	2022	2025	2030	2040	2050
Petrol	below 50 kW	[%]	1.8%	1.8%	1.0%	0.0%	0.0%	0.0%	0.0%
	50-100 kW	[%]	30.9%	28.3%	27.4%	18.0%	0.0%	0.0%	0.0%
	101-200 kW	[%]	44.4%	41.5%	40.0%	35.5%	0.0%	0.0%	0.0%
	above 200 kW	[%]	14.4%	14.4%	11.4%	2.4%	0.0%	0.0%	0.0%
Diesel	below 50 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	50-100 kW	[%]	4.0%	2.8%	2.0%	1.0%	0.0%	0.0%	0.0%
	101-200 kW	[%]	3.3%	2.1%	1.7%	1.0%	0.0%	0.0%	0.0%
	above 200 kW	[%]	0.5%	0.5%	0.5%	0.5%	0.0%	0.0%	0.0%
PHEV / Hybrid	below 50 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	50-100 kW	[%]	0.1%	1.2%	1.1%	0.5%	0.0%	0.0%	0.0%
	101-200 kW	[%]	0.1%	1.2%	1.1%	0.5%	0.0%	0.0%	0.0%
	above 200 kW	[%]	0.0%	0.0%	0.03%	0.0%	0.0%	0.0%	0.0%
BEV – Electric	below 50 kW	[%]	0.1%	0.1%	1.4%	4.0%	10.0%	10.0%	10.0%
	50-100 kW	[%]	0.1%	3.0%	5.4%	16.2%	40.0%	40.0%	40.0%
	101-200 kW	[%]	0.1%	2.9%	5.4%	16.2%	40.0%	40.0%	40.0%
	above 200 kW	[%]	0.0%	0.0%	1.4%	4.0%	10.0%	10.0%	10.0%
Fuel cell / Hydrogen	below 50 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	50-100 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	101-200 kW	[%]	0.0%	0.0%	0.01%	0.0%	0.0%	0.0%	0.0%
	above 200 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other (LPG/ Ethanol etc)	below 50 kW	[%]	0.0%	0.0%	0.01%	0.0%	0.0%	0.0%	0.0%
	50-100 kW	[%]	0.2%	0.2%	0.2%	0.2%	0.0%	0.0%	0.0%
	101-200 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	above 200 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The projected global road transport service demand in passenger kilometres is assumed to remain at the current level of about 42.5 billion kilometres per year – roughly the same as average demand over the past ten years. The assumption is that the average number of passengers per vehicle will drop from 2.5 in 2020 to 2 in 2050. This is due to increased ownership of vehicles in developing countries, where the current number of passengers per vehicle is significantly higher than in OECD countries. Average annual mileage per vehicle is assumed to decrease only slightly from around 15,000 km in 2020 to 13,400 km in 2050, also as an effect of increased ownership in developing countries, resulting in fewer people sharing a single vehicle (Table 6).

Table 6:
Assumed development of transport demand for passenger cars

Transport Service Demand	Unit	2022	2025	2030	2040	2050
Total passenger kilometres per year	[million pkm]	43,957,63	42,652,04	42,500,00	42,500,00	42,500,00
Average annual kilometres per vehicle	[km/vehicle yr]	15,085	14,075	14,675	13,917	13,389
Average number of passengers per vehicle	[1]	2.5	2.5	2.25	2.125	2

Table 7 shows the average CO_2 emissions per ICE vehicle class for the base year 2019. It is assumed that all ICE vehicle classes have an annual fuel efficiency progress of 0.75%. Consequently, calculated fuel demand for new vehicles changes every year. Electric vehicles are assumed to have a slightly higher efficiency progress of 1% per year as the technology is still in an earlier stage of development.

New vehicles with a specific amount of fuel or electricity demand for the year of sale are then assumed to have an average lifespan of 15 years. Table 8 shows that the fuel consumption of a petrol ICE vehicle with 100 kW engine power sold in 2020 is calculated to be 4.8 litres per 100 km until 2035. However, the fuel consumption of the same vehicle class sold in 2025 is assumed to be 4.6 litres per 100km until 2040.

Table 7:
Current average specific CO_2 emissions per kilometre and vehicle class

LDV Average emissions in [gCO_2/km]		Unit	2019
Petrol	below 50 kW	[g CO_2/km]	93.2
	50-100 kW	[g CO_2/km]	128.2
	101-200 kW	[g CO_2/km]	233.0
	above 200 kW	[g CO_2/km]	291.3
Diesel	below 50 kW	[g CO_2/km]	94.0
	50-100 kW	[g CO_2/km]	129.2
	101-200 kW	[g CO_2/km]	235.0
	above 200 kW	[g CO_2/km]	293.7
PHEV / Hybrid	below 50 kW	[g CO_2/km]	93.2
	50-100 kW	[g CO_2/km]	128.2
	101-200 kW	[g CO_2/km]	233.0
	above 200 kW	[g CO_2/km]	291.3
Other (LPG / Ethanol etc)	below 50 kW	[g CO_2/km]	44.6
	50-100 kW	[g CO_2/km]	61.4
	101-200 kW	[g CO_2/km]	111.6
	above 200 kW	[g CO_2/km]	205.0

Table 8:
Assumed development of fuel and electricity consumption for vehicle classes analyzed.

LDV – New vehicles		Unit	Efficiency gains per year	Average emissions in [g CO_2/km]	2020	2025	2030	2040	2050
Petrol	below 50 kW	[l/100km]	0.75%	93.2	3.6	3.5	3.3	3.1	2.9
	50-100 kW	[l/100km]	0.75%	128.2	4.9	4.8	4.6	4.3	3.9
	101-200 kW	[l/100km]	0.75%	233.0	9.0	8.7	8.3	7.7	7.2
	above 200 kW	[l/100km]	0.75%	291.3	11.2	10.8	10.4	9.7	9.0
Diesel	below 50 kW	[l/100km]	0.75%	94.0	3.2	3.1	3.0	2.8	2.6
	50-100 kW	[l/100km]	0.75%	129.2	4.4	4.2	4.1	3.8	3.5
	101-200 kW	[l/100km]	0.75%	235.0	8.0	7.7	7.4	6.9	6.4
	above 200 kW	[l/100km]	0.75%	293.7	10.0	9.6	9.3	8.6	8.0
PHEV / Hybrid	below 50 kW	[l/100km]	0.75%	93.2	3.6	3.5	3.3	3.1	2.9
	50-100 kW	[l/100km]	0.75%	128.2	4.9	4.8	4.6	4.3	3.9
	101-200 kW	[l/100km]	0.75%	233.0	9.0	8.7	8.3	7.7	7.2
	above 200 kW	[l/100km]	0.75%	291.3	11.2	10.8	10.4	9.7	9.0
Other: LPG/ Ethanol etc	below 50 kW	[l/100km]	0.75%	44.6	2.4	2.4	2.3	2.1	2.0
	50-100 kW	[l/100km]	0.75%	61.4	3.4	3.2	3.1	2.9	2.7
	101-200 kW	[l/100km]	0.75%	111.6	6.1	5.9	5.7	5.3	4.9
	above 200 kW	[l/100km]	0.75%	205.0	11.2	10.8	10.4	9.7	9.0
CO_2 / kWh electricity – 1.5˚C scenario			[kg/kWh]			0.25	0.135	0.0265	0
BEV - Electric	below 50 kW	[kWh/100km]	1.00%		5.4	5.0	4.7	4.3	3.9
	50-100 kW	[kWh/100km]	1.00%		11.7	10.7	10.2	9.2	8.4
	101-200 kW	[kWh/100km]	1.00%		16.6	15.3	14.5	13.1	11.9
	above 200 kW	[kWh/100km]	1.00%		22.5	20.7	19.6	17.8	16.1
Fuel Cell / Hydrogen	below 50 kW	[kWh/100km]	1.00%		10.8	9.9	9.4	8.5	7.7
	50-100 kW	[kWh/100km]	1.00%		23.4	21.5	20.4	18.5	16.7
	101-200 kW	[kWh/100km]	1.00%		33.3	30.6	29.1	26.3	23.8
	above 200 kW	[kWh/100km]	1.00%		45.0	41.3	39.3	35.5	32.1

Finally, the CO_2 emission factors per litre of petrol, diesel and LPG shown in Table 9 remain stable throughout the entire modelling period. Efficiency gains in fuel consumption impact the ratio of kilometres driven per litre of fuel. However, the amount of CO_2 per litre of burned fuel remains unchanged because it is a chemical constant.

Table 9:
Emission factors per litre[18]

Petrol	[kg CO_2/l]	2.33
Diesel	[kg CO_2/l]	2.64
LPG	[kg CO_2/l]	1.64

2.5 A 1.5˚C compatible light-duty vehicle market trajectory

Under the assumptions provided in section 2.4, calculated with the methodology described in section 2.3, the LDV market will have to change significantly to remain within the identified carbon budget to limit global mean temperature rise to a maximum of 1.5˚C.

Table 10 shows the calculated global LDV sales by vehicle class that are possible before the carbon budget is exceeded. The limit for petrol- and diesel-fuelled ICE vehicles will already be reached in 2029. If BEVs replace ICE vehicles while the overall LDV sales remain at around 75 million vehicles per year, the BEV market will need to attain ICE manufacturing levels by 2025. Over 2 billion new electric vehicles need to be produced by 2050 – not only to replace ICE LDVs in the new sales segment but also to replace old ICE vehicles at the end of their lifetime.

18 UBA. (2022) Umweltbundesamt Climate Change, 28/2022, CO2-Emissionsfaktoren für fossile Brennstoffe, Aktualisierung 2022. Available online: https://www.umweltbundesamt.de/publikationen/co2-emissionsfaktoren-fuer-fossile-brennstoffe-0

Aerial view of protest against Volkswagen's
ICE exports in the Port of Emden in Germany, 2021
© Greenpeace

Table 10:
Calculated global annual LDV sales by vehicle class

Annual LDV sales in million		2020	2025	2030	2035	2040	2050
Petrol	below 50 kW	0.75	0.00	0.00	0.00	0.00	0.00
	50-100 kW	20.53	13.50	0.00	0.00	0.00	0.00
	101-200 kW	30.00	26.63	0.00	0.00	0.00	0.00
	above 200 kW	8.53	1.78	0.00	0.00	0.00	0.00
Total Petrol Engines		59.81	41.91	0.00	0.00	0.00	0.00
Diesel	below50 kW	0.00	0.00	0.00	0.00	0.00	0.00
	50-100 kW	1.53	0.75	0.00	0.00	0.00	0.00
	101-200 kW	1.28	0.75	0.00	0.00	0.00	0.00
	above 200 kW	0.40	0.40	0.00	0.00	0.00	0.00
Total Diesel Engines		3.21	1.90	0.00	0.00	0.00	0.00
PHEV / Hybrid	below 50 kW	0.00	0.00	0.00	0.00	0.00	0.00
	50-100 kW	0.83	0.34	0.00	0.00	0.00	0.00
	101-200 kW	0.83	0.34	0.00	0.00	0.00	0.00
	above 200 kW	0.02	0.02	0.00	0.00	0.00	0.00
Total PHEV		1.67	0.70	0.00	0.00	0.00	0.00
BEV – Electric	below 50 kW	1.02	3.04	7.50	7.50	7.50	7.50
	50-100 kW	4.07	12.14	30.00	30.00	30.00	30.00
	101-200 kW	4.07	12.14	30.00	30.00	30.00	30.00
	above 200 kW	1.02	3.04	7.50	7.50	7.50	7.50
Total BEV	0	10.17	30.36	75.00	75.00	75.00	75.00
Fuel Cell / Hydrogen	below 50 kW	0.00	0.00	0.00	0.00	0.00	0.00
	50-100 kW	0.00	0.00	0.00	0.00	0.00	0.00
	101-200 kW	0.00	0.00	0.00	0.00	0.00	0.00
	above 200 kW	0.00	0.00	0.00	0.00	0.00	0.00
Total Hydrogen		0.00	0.00	0.00	0.00	0.00	0.00
Other (LPG/Ethanol etc.)	below 50 kW	0.01	0.01	0.00	0.00	0.00	0.00
	50-100 kW	0.13	0.13	0.00	0.00	0.00	0.00
	101-200 kW	0.00	0.00	0.00	0.00	0.00	0.00
	above 200 kW	0.00	0.00	0.00	0.00	0.00	0.00
Total other		0.13	0.13	0.00	0.00	0.00	0.00
Total accumulative LDV sales – from 2022		75.00	301.24	676.10	1050,70	1,426.05	2,185.97
Total annual LDV sales		75.00	75.00	75.00	75.00	75.00	75.00

Table 11 shows annual new LDV sales in millions per year and the number of retired vehicles broken down to energy supply sources and drivetrains. The gradual displacement of combustion engines from road traffic will begin as early as 2025. By 2029, only 14.6 million petrol-fuelled ICE LDVs will enter the market, while 2030 marks the market closure. In 2030, 54.9 million ICE LDVs will retire and be replaced mainly by BEVs.

Table 11:
Global annual LDV sales versus retirement by drive train

Result Annual LDV sales and retirements by technology		Unit	2021	2022	2025	2030	2035	2040	2050
Petrol	sales	[million vehicles/yr]	69.7	59.8	41.9	0.0	0.0	0.0	0.0
	retirements	[million vehicles/yr]	-55.6	-54.2	-54.9	-54.9	-54.9	-33.7	-10.8
Diesel	sales	[million vehicles/yr]	4.4	3.2	1.9	0.0	0.0	0.0	0.0
	retirements	[million vehicles/yr]	-5.2	-5.1	-5.2	-5.1	-4.9	-2.3	-0.1
PHEV / Hybrid	sales	[million vehicles/yr]	1.9	1.7	0.7	0.0	0.0	0.0	0.0
	retirements	[million vehicles/yr]	-0.2	-0.3	-0.5	-0.4	-0.3	0.0	0.0
BEV - Electric	sales	[million vehicles/yr]	4.8	10.9	31.3	75.8	75.5	76.0	85.9
	retirements	[million vehicles/yr]	-0.2	-0.2	-0.2	-0.2	-0.2	-24.3	-60.0
Fuel Cell / Hydrogen	sales	[million vehicles/yr]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	retirements	[million vehicles/yr]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other (LPG/ Ethanol etc)	sales	[million vehicles/yr]	0.1	0.1	0.1	0.0	0.0	0.0	0.0
	retirements	[million vehicles/yr]	-0.2	-0.2	-0.2	-0.2	-0.1	0.0	0.0
Total annual sales		[million vehicles/yr]	81.0	75.7	75.7	75.9	75.8	75.5	76.0
Total annual retirements		[million vehicles/yr]	-61.3	-60.0	-60.0	-60.9	-60.8	-60.5	-60.4

Figure 3 shows that the carbon budget for new petrol-fuelled ICE LDVs allows the manufacturing of 302.1 million additional vehicles (base year 2022), while for diesel-fuelled LDVs, the limit is already reached after 12.4 million (Figure 4) between 2022 and 2050. So to stay within a 1.5°C-compatible carbon trajectory, about 315 million ICE cars and vans can still be sold.

The BEV market will have to increase from around 5 million vehicles in 2021 to 10.9 million in 2022 – within the same level given in the 2022 forecast by Bloomberg New Energy Finance, which estimates 10.5 million BEVs for that year.[19]

19 BNEF (2022), Bloomberg New Energy Finance, Vehicle Outlook 2022, accessed 25.9.2022, https://about.bnef.com/electric-vehicle-outlook/

Figure 3:
Global limit for new petrol LDVs under the Paris Climate Agreement

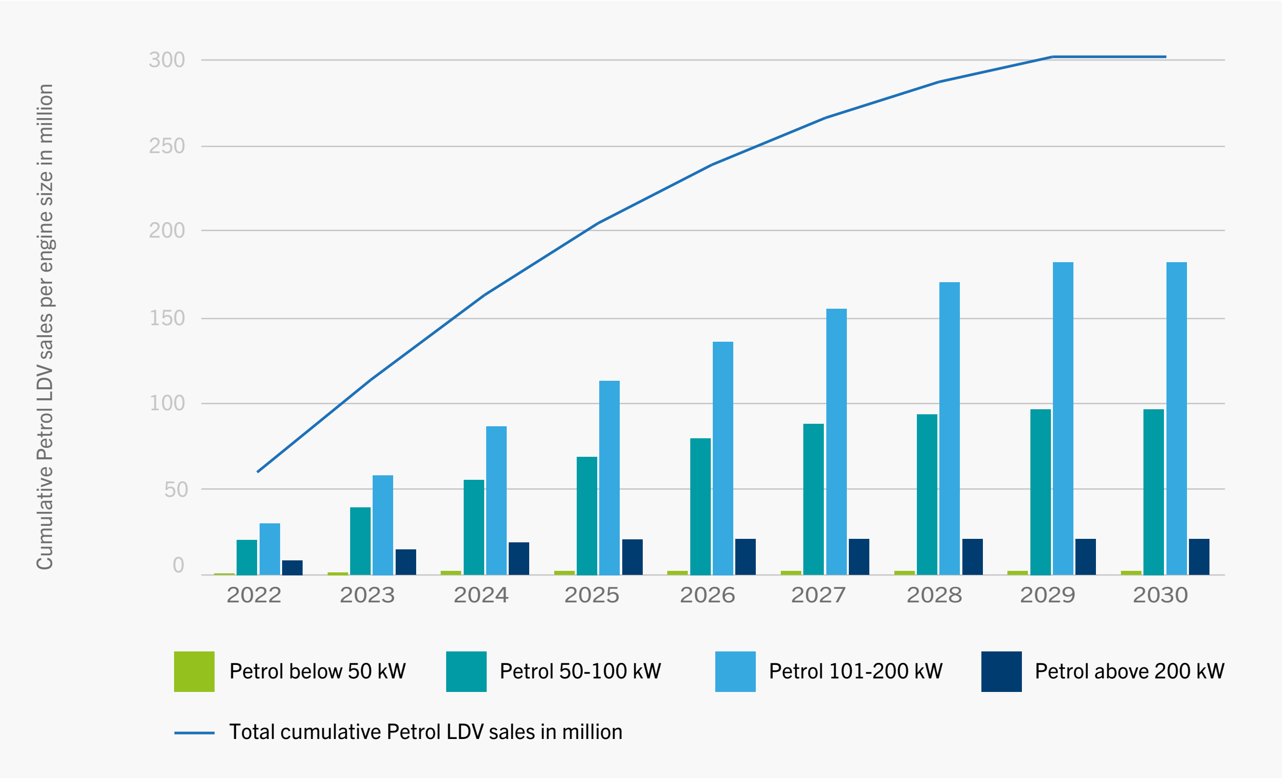
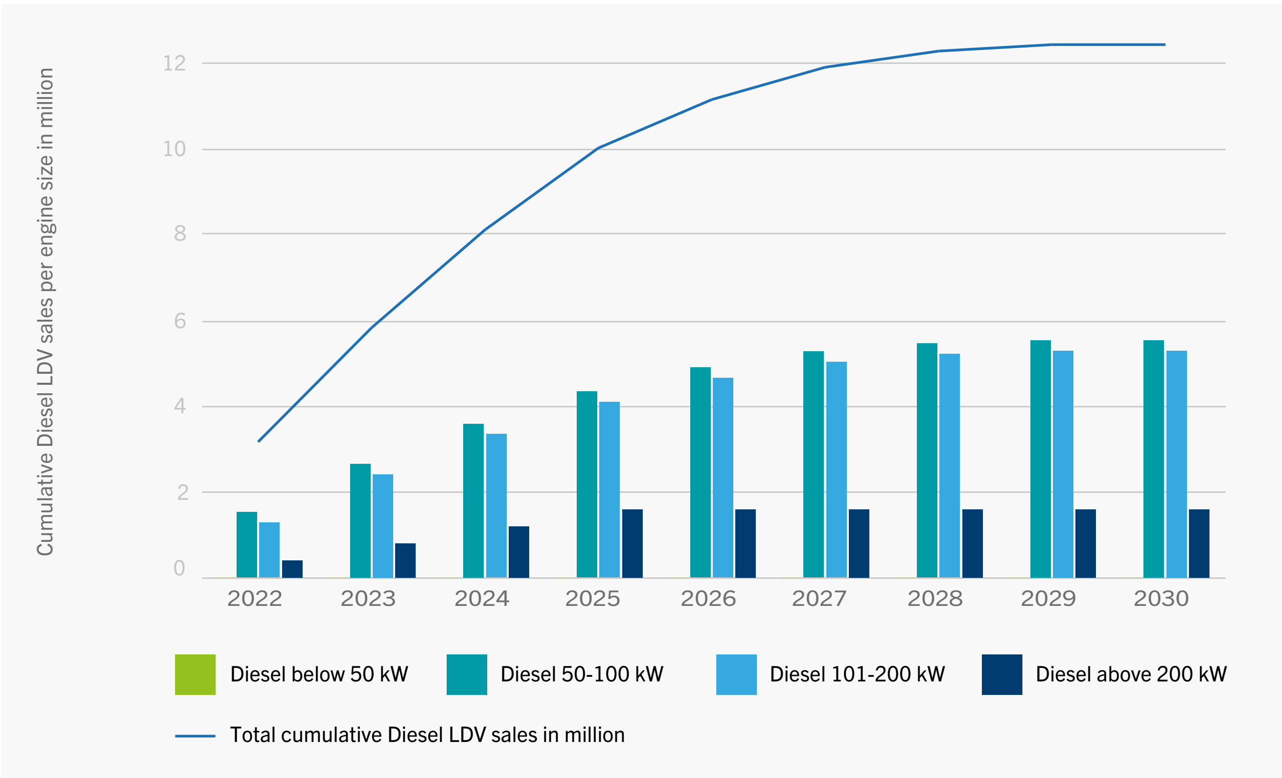


Figure 4:
Global limit for new diesel LDVs under the Paris Climate Agreement



The rate to replace existing fossil fuelled ICE LDV fast enough in order to remain within the carbon budget needs to be around 80% from 2025 on. This high replacement rate needs to be maintained until 2050 to achieve full decarbonization of the LDV fleet. Figure 5 shows new LDV sales and retirements by drivetrain until 2050.

Figure 5:
Global annual LDV sales and retirements

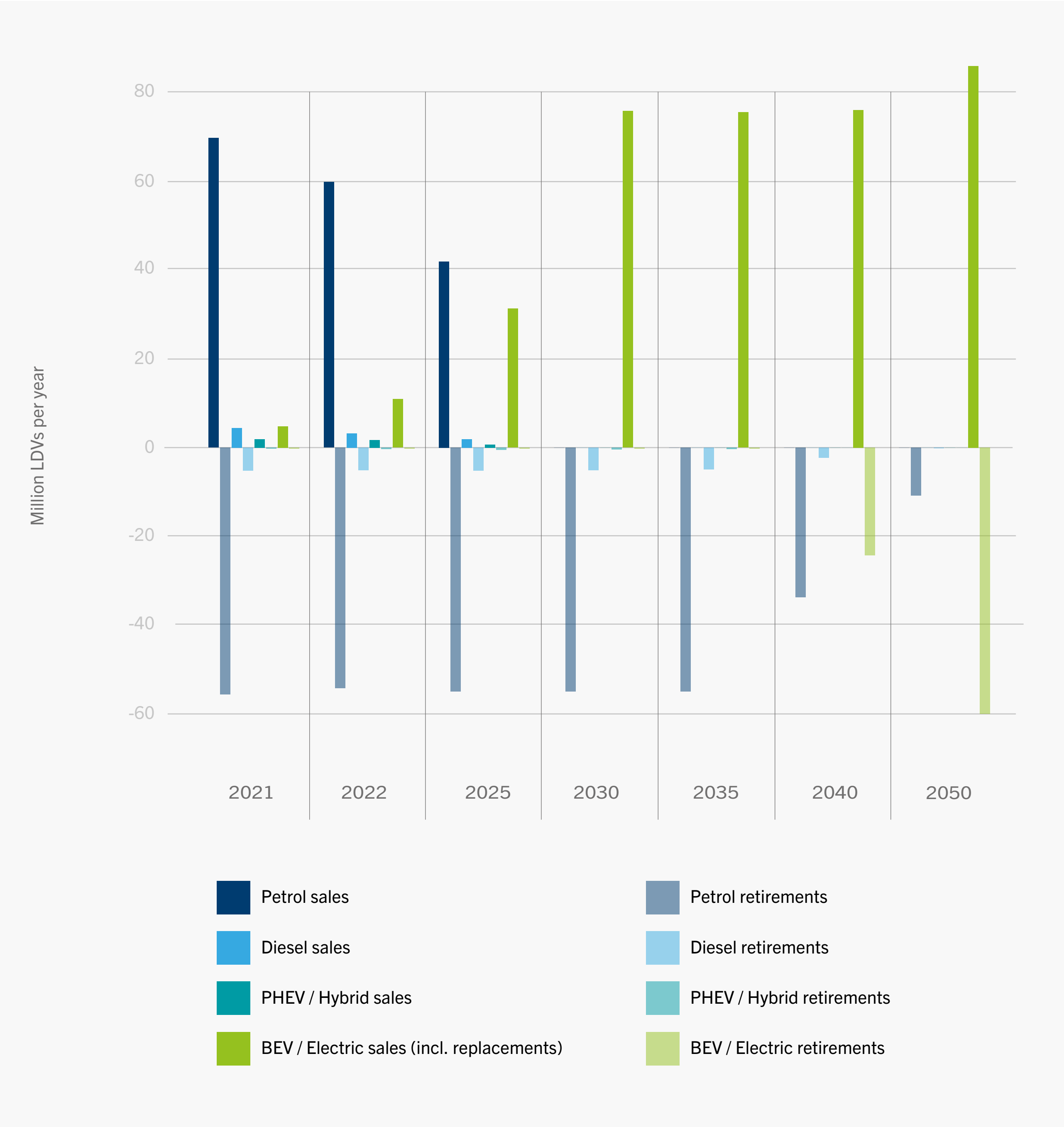


Table 12 shows the annual global CO_2 emissions of the LDV fleet as well as the cumulative emissions between 2020 and 2050. About one-third of all CO_2 emissions from fossil-fuelled ICE vehicles will be emitted after their production ceases in 2030. The replacement of ICEs will be highly prioritised after 2030 to remain within the carbon budget.

Table 12:
Global CO2 emissions from LDV vehicles by technology

Light-Duty Vehicles			2022	2025	2030	2035	2040	2050	2020 - 2030	2020 - 2050
CO_2 / kWh electricity – 1.5˚C Scenario		[kg/kWh]	0.406	0.25	0.135	0.057	0.0265	0		
Petrol	below 50kW	[Mt CO_2]	30	25	18	9	5	1	278	388
	50-100 kW	[Mt CO_2]	678	607	493	293	178	2	6,768	10,394
	101-200 kW	[Mt CO_2]	1,659	1,526	1,339	838	505	65	17,155	27,803
	above 200 kW	[Mt CO_2]	659	550	388	202	134	1	6,094	8,579
Diesel	below 50 kW	[Mt CO_2]	0	0	0	0	0	0	0	0
	50-100 kW	[Mt CO_2]	73	53	31	7	1	0	618	711
	101-200 kW	[Mt CO_2]	124	104	77	41	29	2	1,165	1,714
	above 200 kW	[Mt CO_2]	39	37	27	13	5	0	386	541
PHEV / Hybrid	below 50 kW	[Mt CO_2]	0	0	0	0	0	0	0	0
	50-100 kW	[Mt CO_2]	15	6	1	1	0	0	77	113
	101-200 kW	[Mt CO_2]	28	11	2	2	0	0	138	200
	above 200 kW	[Mt CO_2]	2	2	1	1	0	0	16	21
BEV - Electric	below 50 kW	[Mt CO_2]	3	6	7	3	2	0	53	91
	50-100 kW	[Mt CO_2]	28	48	65	25	15	0	475	800
	101-200 kW	[Mt CO_2]	40	69	92	35	21	0	677	1,140
	above 200 kW	[Mt CO_2]	13	23	31	12	7	0	220	375
Fuel Cell / Hydrogen	below 50 kW	[Mt CO_2]	0	0	0	0	0	0	0	0
	50-100 kW	[Mt CO_2]	0	0	0	0	0	0	0	0
	101-200 kW	[Mt CO_2]	0	0	0	0	0	0	1	1
	above 200 kW	[Mt CO_2]	0	0	0	0	0	0	0	0
LPG & Ethanol	below 50 kW	[Mt CO_2]	0	0	0	0	0	0	1	1
	50-100 kW	[Mt CO_2]	2	2	1	1	0	0	20	28
	101-200 kW	[Mt CO_2]	0	0	0	0	0	0	1	1
	above 200 kW	[Mt CO_2]	0	0	0	0	0	0	0	0
Total Emissions Light-Duty Vehicles		[Mt CO_2]	3,393	3,063	2,560	1,476	898	71	34,144	52,902

Greenpeace Japan activists displayed a banner in front of Toyota Motor Corporation's Annual General Meeting that called on the company to stop producing fossil fuel cars and protect the climate. 2022
© Taishi Takahashi / Greenpeace

3. Projecting the global market volume for internal combustion engine vehicles based on manufacturer announcements

In Chapter 2, we calculated a 1.5°C compliant residual budget based on the sectoral CO_2 budget for the transport sector, which allows a maximum of 315 million LDVs with internal combustion engines to be sold by 2030. In this chapter, we analyze the sales plans of the four leading automakers. The aim is to estimate the planned sales of cars with internal combustion engines (ICE) based on the announced ramp-up scenarios of electromobility.

3.1 Methodology to identify projected global sales of internal combustion engine light-duty vehicles

Forecasting planned ICE sales is not an easy task and depends on many factors. In addition to auto manufacturers' planning, other factors such as market developments and exogenous variables like the COVID-19 pandemic play a considerable role. To ensure the reliability of the results of the following analysis, the assumptions made for the projections of ICE sales are as conservative as possible. In other words, they favour manufacturers so that the estimates presented for planned ICE sales are to be regarded as a lower bound of the auto manufacturers' ICE sales plans.

Accordingly, the estimates for future global ICE sales are based on the following assumptions:

- After the recovery of sales to pre-pandemic levels, no further growth is assumed. That means that global auto sales for LDVs will rise to 85 million vehicles by 2022, the same as in 2019, and ultimately remain at that level. While GM and Asian manufacturers Toyota and Hyundai/Kia regained their pre-crisis levels in 2021, Volkswagen's sales are recovering more slowly as disturbed supply chains following Russia's invasion of Ukraine added to the microchip supply bottleneck.

- New market entrants and all-electric auto companies such as Tesla were excluded from the analysis and have not been examined. This modelling is based on the – hypothetical – assumption that established auto companies will not lose any market share to new all-electric manufacturers.

- No downsizing: Another assumption is that manufacturers will not change the composition of their

ICE model portfolios. In other words, the historical trend towards heavier and more powerful vehicles will not continue, nor will it be reversed in favour of smaller and lighter ICE vehicles.

- No biofuels or synthetic fuels: In line with the assumptions made for the calculation of the 1.5°C budget for internal combustion LDVs in Chapter 2, there is no expansion in the use of biofuels to reduce emissions nor do synthetic fuels play any significant role in road transport.

- The projection of global development is based on the assessment of four manufacturers: Toyota, Volkswagen, Hyundai/Kia, and GM, whose sales plans are analyzed in detail. The assumption is that these four companies, with a global market share of around 40%, constitute a representative sample of the global automotive market.

- Most manufacturers have provided only limited information on their BEV plans. To obtain robust results, three different scenarios, a linear and an exponential pathway based on an S-curve, and a combination of these two curves have been developed for each manufacturer based on the targets and plans they have published. This results in a total of 12 alternative pathways for the ramp-up of production and sales of BEVs, used in a second step to approximate global transition scenarios.
  The global ramp-up scenarios for BEVs, in combination with assumed total global sales, allow the identification of manufacturers' implied planned sales of internal combustion engine light-duty vehicles.

- We have used the manufacturers' announcements to estimate BEV production and sales ramp-up. However, manufacturers have made very limited statements on global plans. We have therefore included announcements linked to specific regions where we do not have further specifications. Hence, this approach favours the auto manufacturers since their commitments for the more developed markets have been applied to all global markets. In fact, several manufacturers are proclaiming the opposite – that ICE vehicles can and will be sold in certain regions far beyond 2040.

- Although no global phase-out dates for internal combustion technology by 2040 have been communicated by three of the four manufacturers examined, it is assumed that they will produce emission-free LDV from 2040 onwards. This assumption is not consistent with the manufacturers' statements since they expect to sell internal combustion vehicles in less developed markets beyond 2040.
  Therefore, the transition to BEVs could also be lower than estimated, as we extrapolated the announcements made by some of the manufacturers that referred only to key markets such as China, the EU and the US to the entire global market, including developing countries.

3.2 Analysis of companies' sales plans and electric vehicle pledges

Companies are adopting different approaches when communicating their transition plans. While some manufacturers disclose only a few details of their strategy and sometimes communicate very vague phase-out dates for internal combustion engines in the distant future, other manufacturers tend to publish a detailed strategy, including numerous intermediate milestones. Only General Motors has communicated an exact global phase-out date - 2035. Hyundai/Kia refers to phasing out ICE by 2040 in "major markets", with only KIA commiting to phasing out ICE globally by 2045.

Table 13:
Announced global ICE phase-out dates:

VW Group	Toyota	Hyundai / Kia	GM
No date (Initially announced 2040, but stopped communicating this date)	No date	2040: "For major markets" (Hyundai & KIA) 2045: "all global markets" (KIA only)	2035

After initially announcing a 2040 phase-out,[20] the Volkswagen Group now refuses to commit to a global phase-out date. However, the Volkswagen Group has committed to several intermediate steps. Its brand Audi also announced a transition to BEVs by 2032 but excluded its main market, China.[21] Toyota's plans to phase out ICE vehicles have to date been limited to its luxury brand Lexus, which made up about 7 % of Toyota's total sales in 2021. Toyota aims for Lexus to go all-electric by 2035.[22] In October 2022, the EU passed its revised CO_2 regulation that required automakers to phase out the sale of ICE cars and vans in Europe from 2035 onwards. All manufacturers analysed in this report have announced that they will meet these requirements. Table 14 shows the various milestones in the ramp-up of BEVs based on the plans communicated by manufacturers. The information used is derived from annual reports, investor briefings, press releases and inquiries to the manufacturers.

---

20 Handelsblatt (2018), Handelsblatt Autogipfel, Volkswagen kündigt das Ende des Verbrennungsmotors an, S. Menzel, F. Hubrik; 4. December 2018, https://www.handelsblatt.com/unternehmen/industrie/auto-von-morgen/handelsblatt-autogipfel-volkswagen-kuendigt-das-ende-des-verbrennungsmotors-an/23715746.html

21 Automobilwoche (2021), Audi-Verbrenner ab 2033 nur noch in China, 23. June 2021, last viewed September 22, 2022, https://www.automobilwoche.de/nachrichten/audi-verbrenner-ab-2033-nur-noch-china

22 Toyota (2021), Media Briefing on Battery EV Strategies, last viewed November 2, 2022, https://global.toyota/en/newsroom/corporate/36428993.html

Table 14:
Communicated BEV production and sales goals[22]

		Volkswagen	General Motors	Hyundai / Kia	Toyota
Company Announcements	2023		"the company is targeting to sell 400,000 EVs in North American through 2023"		
	2025	20% of global sales to be BEVs	"Over 1 million electric vehicles production capacity in North America and China separately by 2025"		
	2030	50% of global sales to be BEVs	(GM is aiming for a share of 50% of its production capacity in North America to be dedicated to EVs by 2030)	3.07 Million BEVs by 2030 - 1.87 by Hyundai and 1.2 million by Kia	„We aim to achieve global sales of 3.5 million battery EVs per year by 2030“
	2035		"aspiration to eliminate tailpipe emissions from new light-duty vehicles globally by 2035“		
	2040	"nearly 100% zero-emission vehicles in all major markets"		Hyundai: "By 2040, Hyundai will phase out all vehicles using fossil fuels in major markets" Kia: "Our product lineup in Europe will be fully electric by 2035, followed by other major markets by 2040. And ultimately all global markets will be electric by 2045."	
"Translated" BEV-Share		**BEV share**	**BEV share**	**BEV share**	**BEV share**
	2023		8%		
	2025	20%	32%		
	2030	50%		41%	35%
	2035		100%		
	2040	99%*	100%	99%*	99%*

*No phase out date announced

Table 14 lays out the companies' plans and presents their key milestones up to 2040. This "translates" into the graph below showing planned BEV sales both in absolute numbers (left side of each graph) and relative share (right side of each graph).

---

23 Volkswagen AG (2021), Jahrespressekonferenz 16.03.2021, Rede Herbert Diess, last viewed September 22, 2022, https://www.volkswagen-newsroom.com/de/publikationen/reden/reden-jahrespressekonferenz-2021-641/download

Volkswagen AG (2021), New Auto Strategy Presentation, last viewed September 22, 2022, https://www.volkswagenag.com/presence/investorrelation/publications/presentations/2021/07/EN-Herbert%20Diess_Speech%20NEW%20AUTO%20Strategy%20Presentation.pdf

Hyundai (2021), Hyundai Motor Reports 2021 Global Sales and 2022 Goals, last viewed September 22, 2022, https://www.hyundai.com/worldwide/en/company/newsroom/hyundai-motor-reports-2021-global-sales-and-2022-goals-0000016776

Kia (2022), KIA CEO Investor Day – KIA presents 2030 roadmap to become global sustainable mobility leader, last viewed September 22, 2022, https://press.kia.com/eu/en/home/media-resouces/press-releases/2022/Kia-CEO-Investor-Day.html

New York Times (2021), G.M. Will Sell Only Zero-Emission Vehicles by 2035, last viewed September 22, 2022, https://www.nytimes.com/2021/01/28/business/gm-zero-emission-vehicles.html

General Motors (2022), GM fi rst-quarter net profi t hits $2.9 billion, press release from April 27th 2022, last viewed September 22, 2022, https://media.gm.com/media/cn/zh/gm/news.detail.html/content/Pages/news/cn/zh/2022/Apr/0427-gm-q1-earnings.html

CNBC (2022), Key takeaways from GM's Q4 results and 2022 guidance, February 2nd 2022 last viewed September 22, 2022, https://www.cnbc.com/2022/02/02/general-motors-key-takeaways-from-gms-q4-results-and-2022-guidance.html

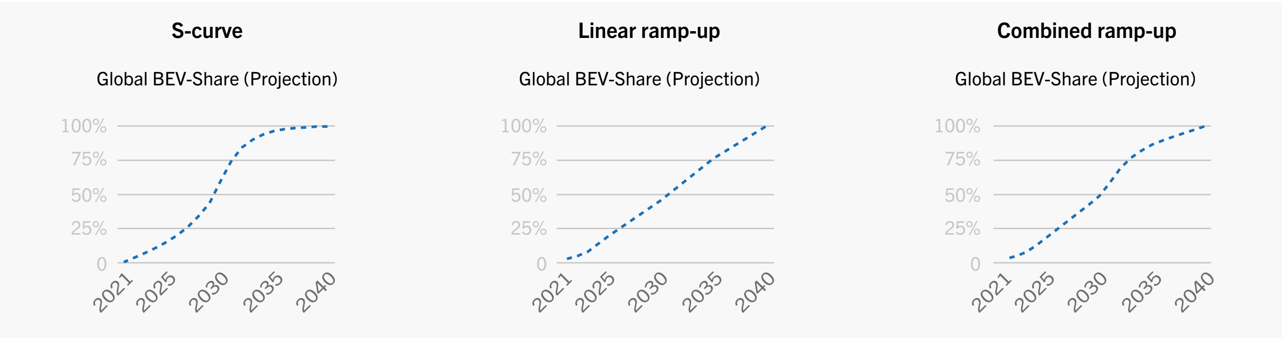
Toyota (2021), Media Briefing on Battery EV from December 14th 2021, last viewed September 22, 2022, https://global.toyota/en/newsroom/corporate/36428993.html

Protest against climate-damaging cars
at the IAA in Frankfurt, 2022

3.3 Estimating internal combustion engine light-duty vehicles sales for Volkswagen, Toyota, Hyundai / Kia and General Motors

Figure 6 shows three possible scenarios for the ramp-up of BEV production over time. The first, an "S-curve" implementation, produces a moderate start as only pioneers and early adopters are involved. A steep ramp-up with significant cost reductions is followed by an exponentially growing user base, and, finally, the curve flattens when market saturation is reached. Furthermore, when entering the plateau phase, only marginal cost reductions materialize.

Figure 6:
Three technological transition scenarios



The second scenario exhibits a linear growth pattern defined by steady growth over time, with no steep ramp-up phase. This analysis sees a "linear" growth pattern as less ambitious than the S-curve scenario. The introduction of the automobile in the USA before 1938, for example, showed a linear growth of the industry.[24] Both the S-curve and linear markets and manufacturing growth require favourable conditions to support and maintain such growth. Looking at the auto industry during the 20th century, we see that the expansion of infrastructures such as roads, petrol stations, and car workshops supported and enabled growth. Today, the introduction of BEVs requires adequate charging infrastructure – a key prerequisite for continued growth. Furthermore, the ramp-up of production capacities, including the required supply chain, significantly influences whether growth rates follow the S-curve or a linear pattern. Supportive policy measures are a major pre-condition to expanding the required BEV infrastructure.

The literature shows no clear preference for an S-curve or a linear growth pattern for technology transitions.[25] Therefore, a third scenario has been calculated: The combination of an S-curve scenario and a linear growth scenario carried out on the basis of the unweighted average of the two. Based on the

---

24 NBER (2022) Macrohistoric Database, St. Louis Fed. Last accessed via Macrobond on September 6th, 2022.

25 Raymond Vernon (1966), International Investment and International Trade in the Product Cycle in: Quarterly Journal of Economics, 1966, pp 190–207 & Arthur D. Little International: Management im Zeitalter der strategischen Führung, Wiesbaden 1986, pp. 52 - 56.

resulting three different scenarios for BEV production, the sales figures for ICE LDVs can be determined based on the assumptions presented in section 3.1. In addition to the annual sales figures, the cumulative sales manufacturers expect up to 2040 are shown in the following graphs under the three growth scenarios (Figures 7, 8 and 9).

Figure 7:
Linear BEV transition scenario

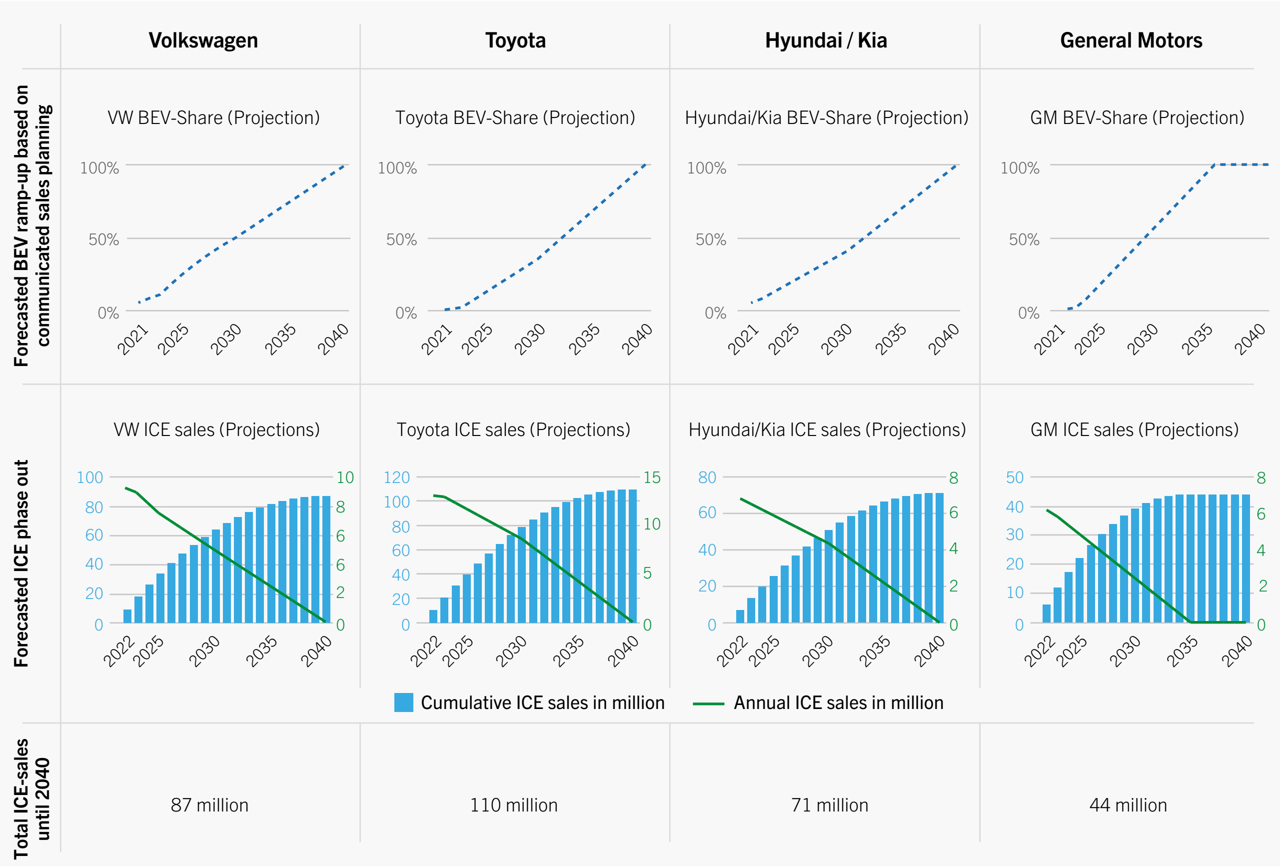


Figure 8: S-curve BEV transition scenario

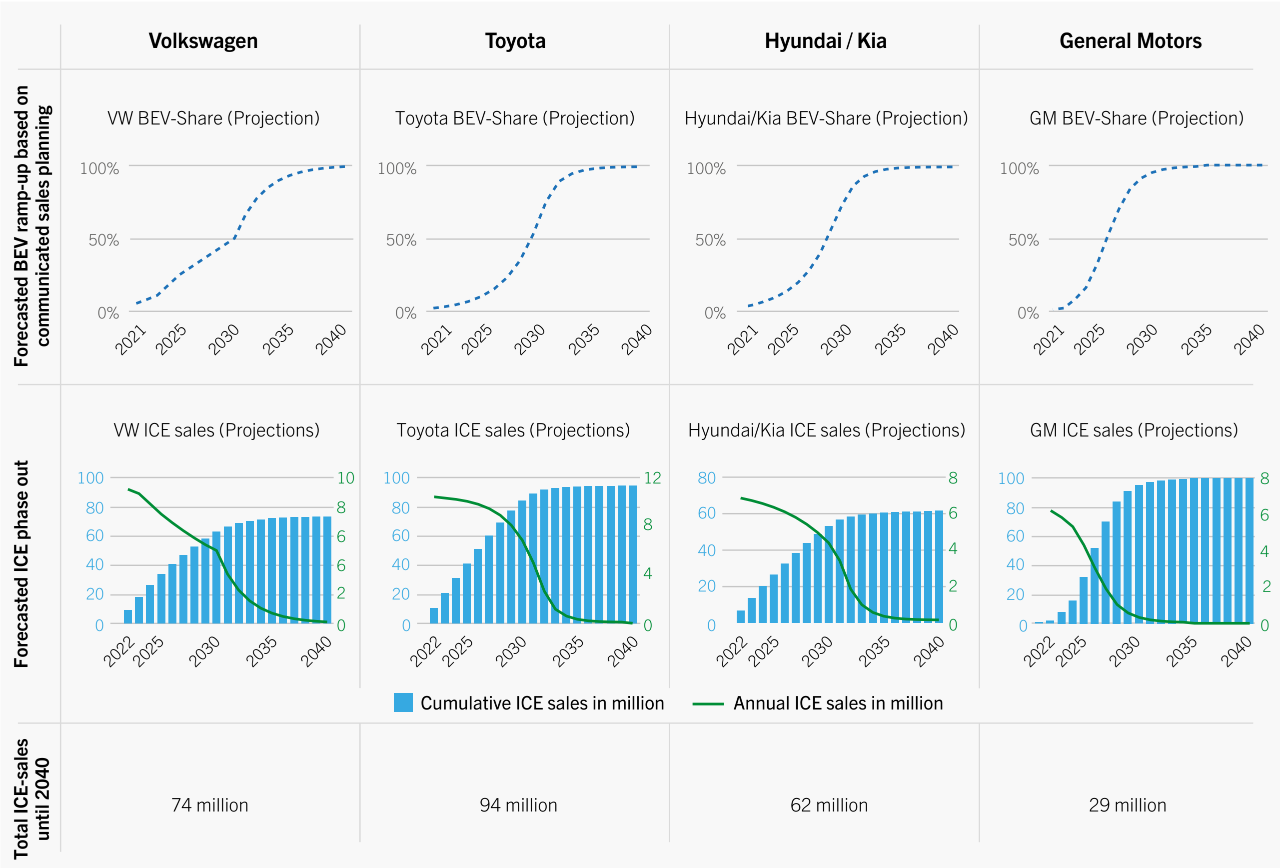
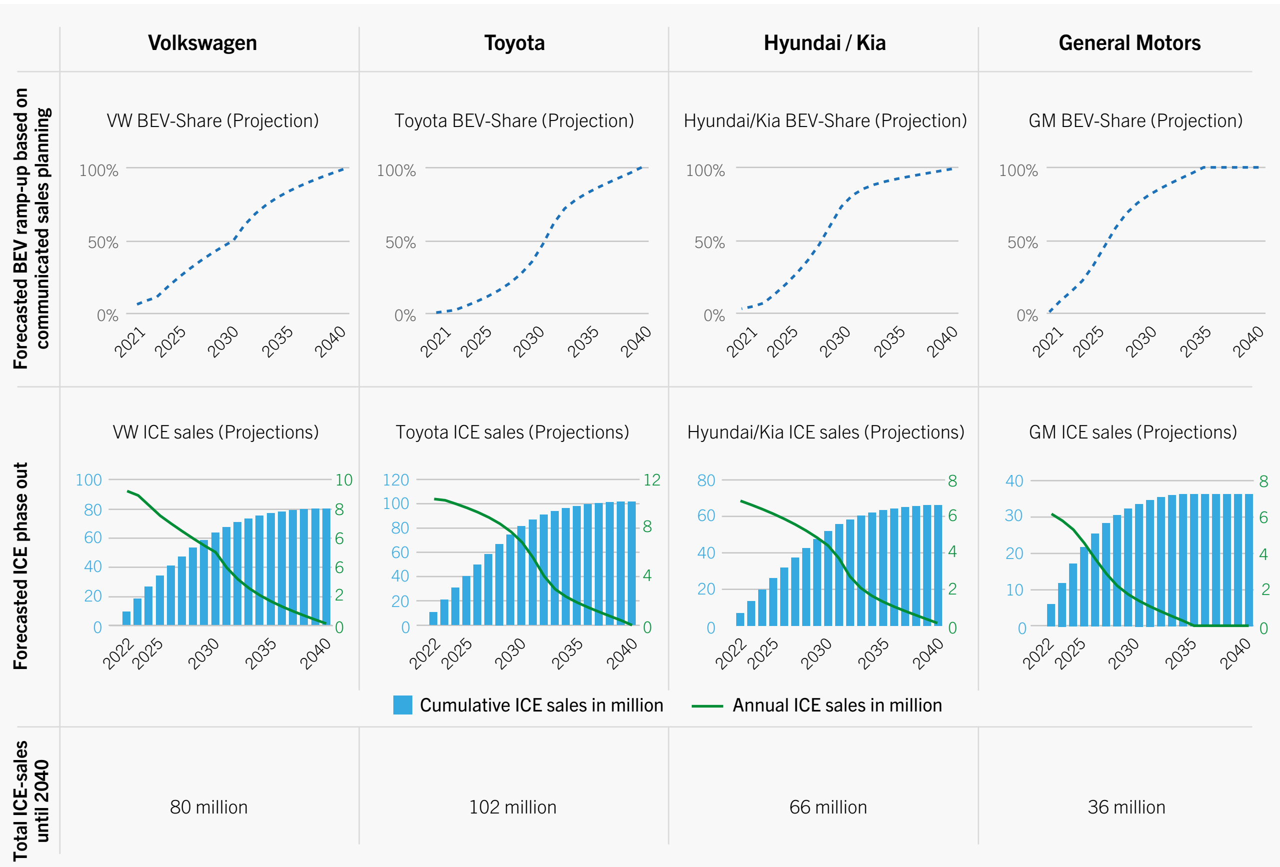


Figure 9: Combined BEV transition scenario



The linear transition can be understood as a pessimistic and slow transition scenario or an upper bound for the number of ICE vehicles manufacturers are still planning to produce. On the other hand, the exponential S-curve ramp-up represents an optimistic scenario for the growth of BEV with fewer ICEs entering the market over time. The S-curve scenario describes the upper, while the linear scenario describes the lower end of the possible development of manufactured ICE vehicles. The combination of both represents the median development defined as a base case in this analysis. Based on the manufacturers' plans, Table 15 shows the overall figures for the planned cumulative sale of ICE vehicles that can be forecasted up to 2040:

Table 15:
Forecasted auto manufacturer plans of total ICE LDV sales up to 2040 in millions

	VW Group	Toyota	Hyundai / Kia	General Motors
Upper bound (linear)	87	110	71	44
Lower bound (S-curve)	74	94	62	29
Base case (combined)	80	102	66	36

The transition scenarios and the resulting cumulative sum of ICE sales of the four auto manufacturers are the basis used to determine global developments. The manufacturers analyzed have 40% of the global market. Their model line-up includes all segments (small, medium and luxury) as mass producers with a broad portfolio. They can thus be regarded as a representative sample of the global automotive market. Therefore, the different results for transition pathways at the company level form the foundations for the calculation of global transition scenarios. The calculation is carried out on the basis of weighted averages, whereby the weighting is based on each manufacturer's respective market share in 2021.

3.4 Projected global ICE vehicle sales

Figure 10:
Global BEV ramp-up (projections)

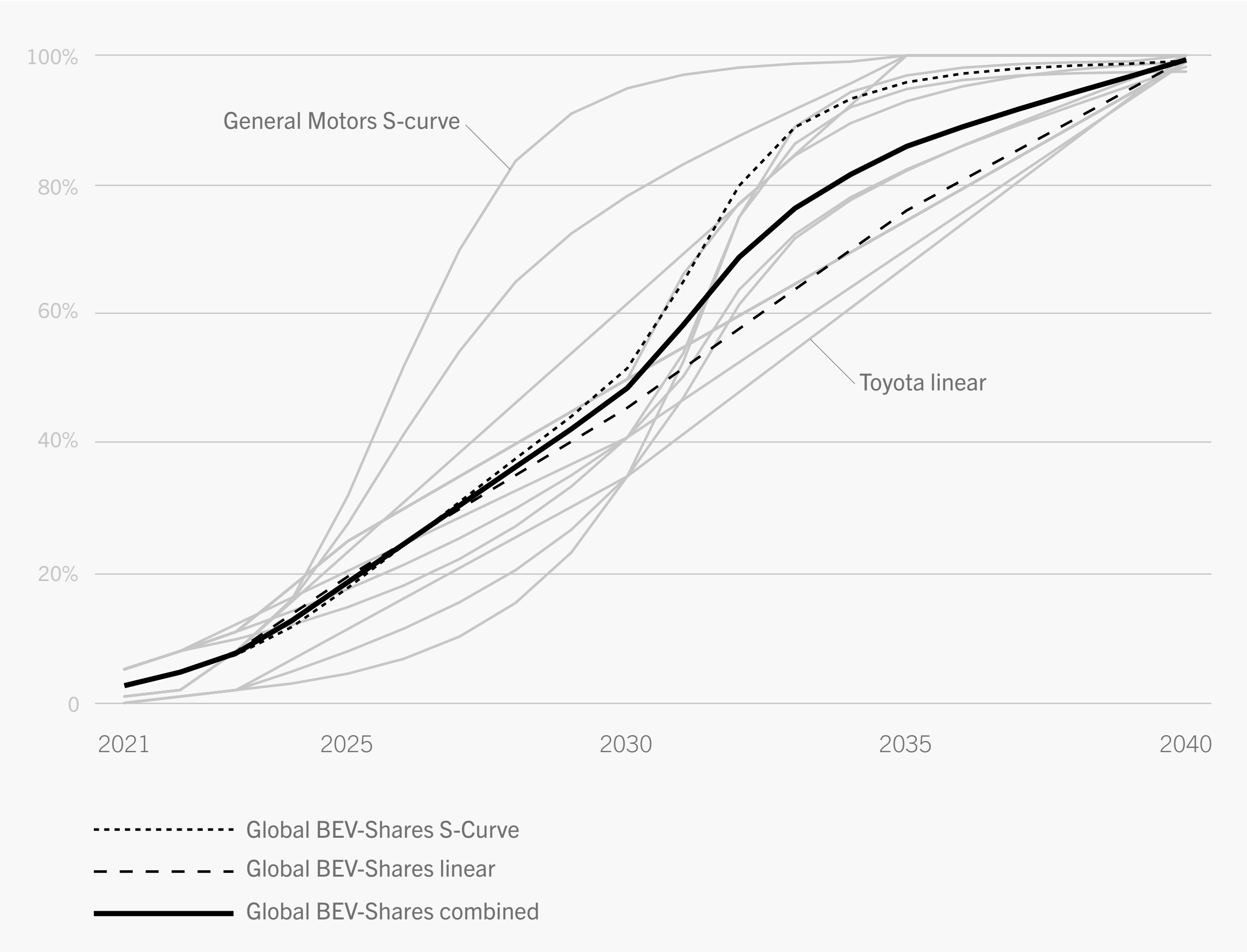
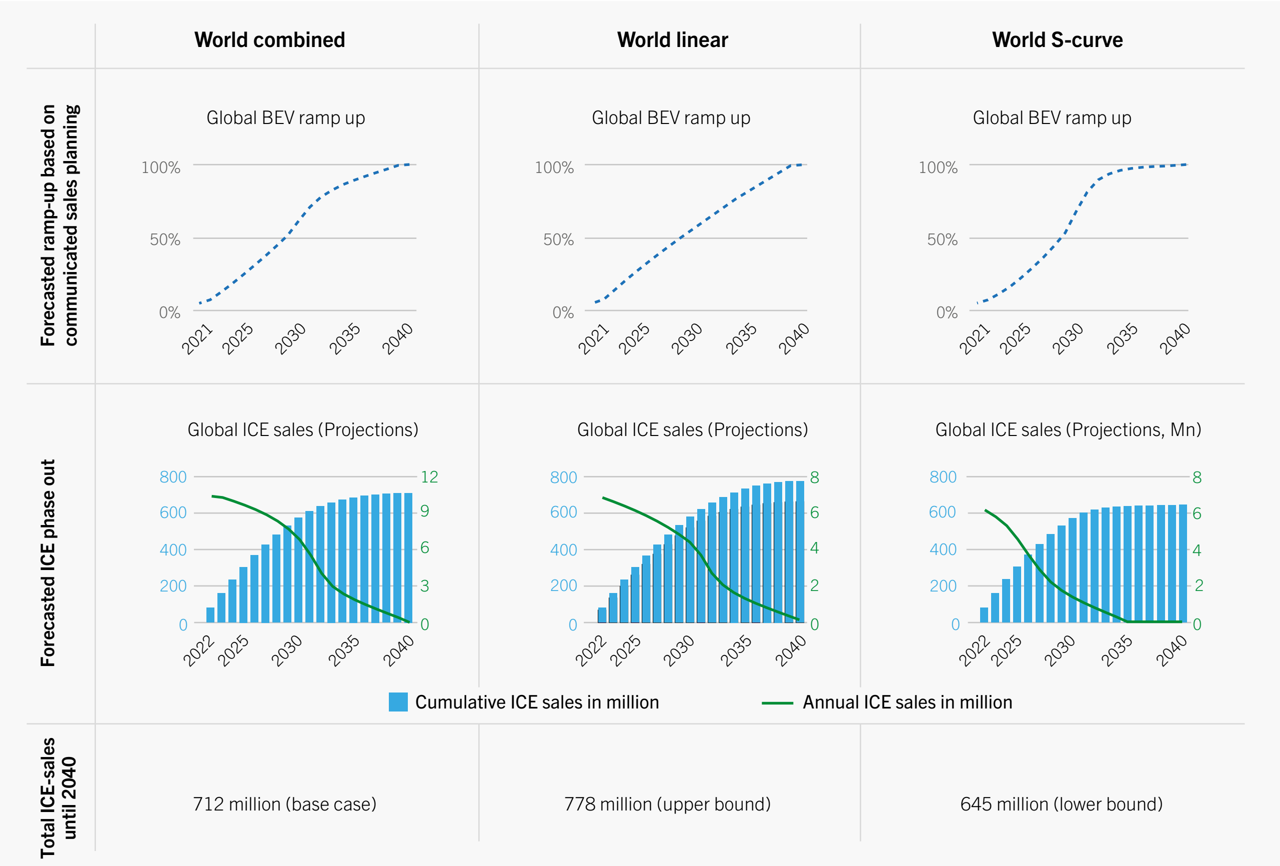


Figure 12 shows the manufacturers' different transition scenarios and the resulting global transition. Toyota's plans are the most conservative, with the linear transition path based on their announcements being the least ambitious. In contrast, GM's plans are the most ambitious. Based on their announcements, the S-curve scenario shows the fastest transition speed.

The global transition scenario is slightly below the (unweighted) average of the four manufacturers due to Toyota's weight as the largest manufacturer. This clearly shows how decisive the plans of the world's largest manufacturers Toyota and Volkswagen are, whose plans are less ambitious plans than GM's. Based on these global BEV transition scenarios, the expected global sales of ICE LDVs can be estimated analogously to the calculations at the individual manufacturer level (see Figure 11). Projected ICE sales range from 645 to 778 million, with 712 million sales as the base case.

Figure 11:
Projected total ICE sales up to 2040



Greenpeace activists put a message “No more internal combustion engines” on an advertisement in front of Hyundai Motor’s HQ building in Seoul, South Korea, 2019.
© Soojung Do / Greenpeace

4. The ICE bubble

Having determined the remaining global number of ICE vehicle sales possible under a 1.5°C carbon budget in Chapter 2 and projected future ICE sales based on current manufacturer plans in Chapter 3, we will now compare the two and identify an ICE bubble – the number of vehicles projected to be sold by manufacturers in excess of what is in line with a 1.5°C-compatible carbon budget.

4.1 The extent of the ICE bubble and its implication for the global carbon budget

Comparing projected ICE LDV sales of 645 to 778 million vehicles - 712 million being the base case - with the number of ICE vehicles that can still be sold within a 1.5°C-compatible carbon budget results in a significant overshoot (see Figure 12 and Table 16).

The cumulative remaining carbon budget for light-duty vehicles with ICE under the 1.5˚C pathway is calculated to be 53 GtCO_2. The calculated ICE phase-out trajectory under the "current policy" scenario will lead to cumulative carbon emissions (2020 to 2050) amounting to a minimum of 98 GtCO_2 and a maximum of 116 GtCO_2. Those overshoot emissions of at least 45 GtCO_2 are in the order of the cumulative carbon budget of the global buildings sector[26] and, therefore, very unlikely to be compensated by other sectors.

26 Chatterjee et al. (2022), Chatterjee, S., Kiss, B., Ürge-Vorsatz, D., Teske, S. (2022). Decarbonisation Pathways for Buildings. In: Teske, S. (eds) Achieving the Paris Climate Agreement Goals. Springer, Cham. https://doi.org/10.1007/978-3-030-99177-7_7

Figure 12:
Global ICE sales projections vs remaining 1,5°C compatible number of ICE sales

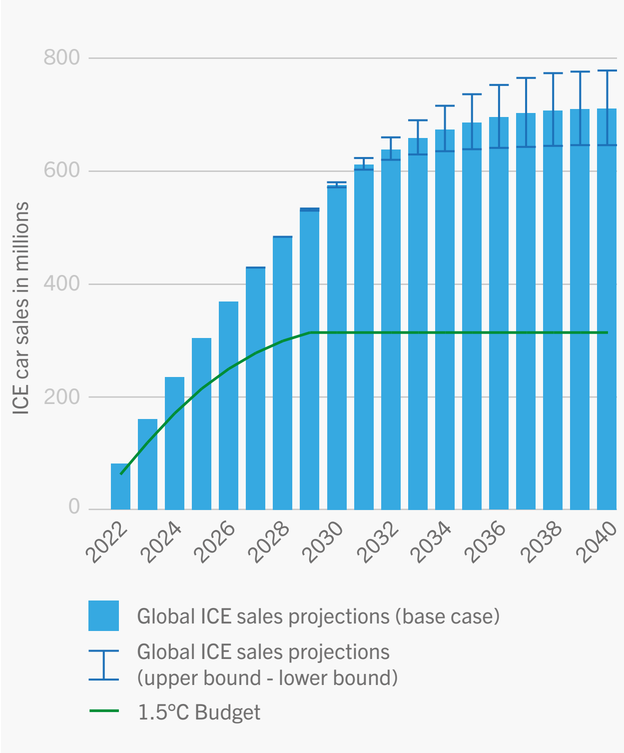


Table 16:
Comparison of global ICE vehicle sales scenarios

		1.5°C-compatible scenario	Projected ICE vehicle sales scenarios		
			lower bound	base	upper bound
Cumulative ICE LDV sales in millions		315	645	712	778
ICE Bubble: sales overshoot over 1.5°C-compatible volume	[million ICEs]		330	397	463
Overshoot in percent	[%]		105%	126%	147%
Total cumulative CO_2 emissions (2020-2050) in million tonnes for the LDV sector	[million t CO_2]	52,902	98,426	107,411	116,532
Cumulation CO_2 emissions – calculated overshoot	[million t CO_2]	-	45,524	54,509	63,630
Calculated overshoot in percent	[%]	-	86%	103%	120%

If governments pursue all efforts to limit warming to 1.5°C, the auto industry will face a serious ICE bubble; in other words, the ICE vehicles the industry plans to sell but will not be able to if the sector is to stay within a 1.5°C trajectory. With a projected 330 to 463 million vehicles, this ICE bubble poses significant risks in the form of stranded assets and losses in market share.

To understand the causes of this overshoot, it is worth looking at the transition rate for electric powertrains, comparing what is needed in the 1.5°C-compatible scenario with projections based on current manufacturers' announcements. Figures 13 and 14 show that traditional manufacturers are planning a much slower BEV transition than required to meet the 1.5°C target. Global car production would have to switch to all-electric cars by 2030 at the latest. However, manufacturers expect a share of only 52% at that time.

Figure 13:
The BEV transition: necessary versus projected BEV shares

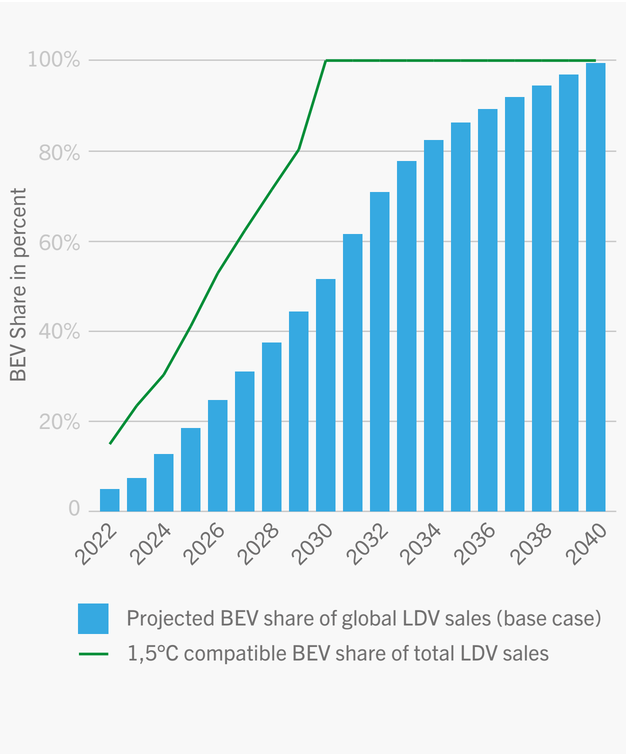
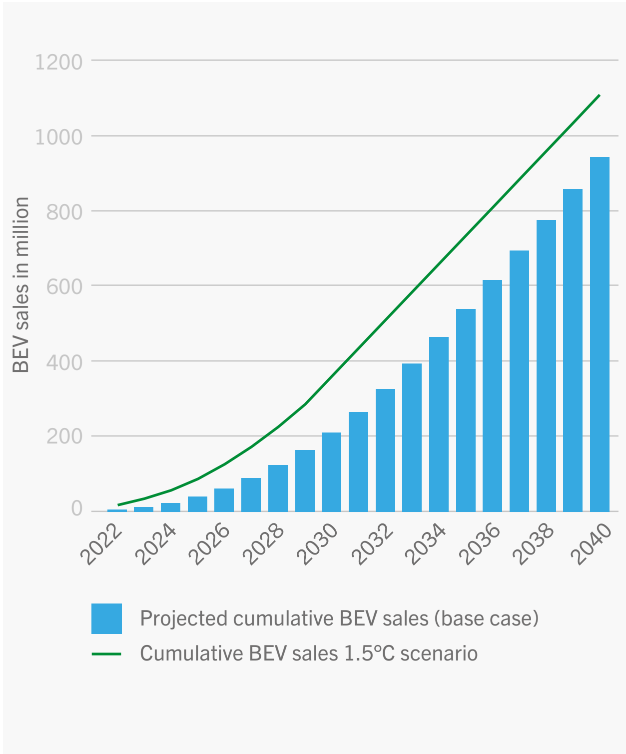


Figure 14:
The BEV transition: necessary versus projected BEV sales



Planning to cover only half of global BEV demand in a 1.5°C aligned LDV market poses a significant risk to traditional automakers. Pure electric car manufacturers have proven that a zero-emission car fleet is already possible, making it easier for policymakers and regulators to accelerate the phase-out of the internal combustion engine in line with the Paris Agreement. Losing market share to these new all-electric competitors is one of the most serious business risks of the ICE bubble for traditional automakers.

4.2 Manufacturer-specific results

Table 17 provides ICE bubble figures specific to each of the four manufacturers.

Table 17:
Expected ICE sales overshoot of key manufacturers relative to a 1.5°C carbon budget

	VW Group	Toyota	Hyundai / Kia	GM
Overshoot in % [lower bound; upper bound]	**118%** [100%; 136%]	**164%** [144%; 184%]	**142%** [124%; 159%]	**57%** [25%; 90%]
Overshoot in million ICE LDV [lower bound; upper bound]	**43 million** [37 million; 50 million]	**63 million** [55 million; 71 million]	**39 million** [35 million; 44 million]	**13 million** [6 million; 21 million]

Volkswagen

The Volkswagen Group sold 452,900 BEVs in 2021. With a global market share of 10 percent, the Volkswagen Group was the third largest BEV manufacturer behind Tesla and SAIC.[27] Volkswagen currently offers 14 BEV models across all its brands (except Lamborghini and Bentley) based on its all-electric MEB and PPE platforms. A follow-up "Scalable Systems Platform" is under development. In June 2020, Volkswagen's factory in Zwickau switched to BEV-only production.[28] The company is in the process of transitioning additional factories to BEV production[29] and is investing in its own battery-cell production, with the first factories set to start production in 2025.[30]

Despite having the best starting position among the companies analyzed, Volkswagen pursues a comparatively slow transition strategy, with – according to the published BEV sales goals of the group – only linear growth until 2030. Hence, according to projections, Volkswagen is planning to sell at least 37 to 50 million or 100% to 136% more ICE vehicles than what is compatible with a 1.5°C scenario.

Toyota

BEVs were initially a side note in Toyota's transition strategy, which focused primarily on full hybrids, plug-in hybrids and FCEVs. A more expansive shift towards BEVs was only announced in December of

27 InsideEV (2022), World's Top 5 EV Automotive Groups Ranked by Sales: 2021, Inside EV, online magazine February 2022, last viewed September 22, 2022, https://insideevs.com/news/564800/world-top-oem-sales-2021/

28 VW (2022a), VW company website, last viewed September 22, 2022, https://www.volkswagen-sachsen.de/de/unternehmen/pressemitteilungen/pm_transformation-schreitet-voran.html

29 VW company website, last viewed September 22, 2022, https://www.volkswagen-newsroom.com/en/press-releases/volkswagens-global-production-network-for-electric-vehicles-grows-with-the-launch-of-a-second-german-site-in-emden-7976

30 German Federal Government (2022), Transformation to a climate-neutral industry, official website of the German Federal Government, viewed September 2022, https://www.bundesregierung.de/breg-en/news/battery-cell-plant-vw-salzgitter-2060434

2021.[31] Toyota currently offers very few BEV models. Over the past two years, an electrified version of its Proace City van, the C+pod (an electric mini-car only offered in Japan), as well as the C-HR and IZOA (two models only offered in China) have become available. Great attention has been given to the bZ4x, Toyota's first mass-market BEV model on its new electric e-TNGA platform offered in China, Europe, the US and Japan, which became available in May 2022. However, the launch of the bZ4x was plagued by problems, leading to a safety recall, and reportedly the model's production capacity is currently limited to 1,000 vehicles a month.[32] Dragging their feet on BEVs for such a long time and planning to sell only about 3.5 million zero-emission vehicles by 2030 (which, according to our assumptions, would merely amount to about one-third of its sales) and not announcing a comprehensive ICE phase-out leaves Toyota with by far the worst performance among the manufacturers analyzed. ICE sales projected to be at least 55 to 71 million or 144% to 184% higher than what is compatible with a 1.5°C scenario are the consequence of this strategy.

Hyundai / Kia

With 216,000 BEVs sold in 2021, Hyundai/Kia was the fifth largest BEV producer globally. Moreover, it had a great start in the US in 2022, outselling every competitor but Tesla.[33] Hyundai, Kia and Genesis (Hyundai/Kia's luxury brand) are currently offering six BEV models. They are planning to rapidly broaden their portfolio, adding at least 30 models by 2030.[34][35] While putting more and more emphasis on BEVs, Hyundai/Kia is pursuing a two-pronged strategy, including fuel-cell electric vehicles (FCEV) in their transition away from the internal combustion engine. Hyundai is currently offering one FCEV model, the Hyundai Nexo, which has been in production since 2018. Due to the lower efficiency compared to BEVs, fuel cell technology in cars is controversial, and many analysts don't believe that the technology can compete with BEVs.[36] The transition away from ICE cars planned by Hyundai/Kia is also too slow, resulting in projected ICE sales that are at least 35 to 44 million or 125% to 159 % higher than needed to be 1.5°C compatible.

---

31 The Drive (2021), Toyota Has a New EV Strategy. Here's Where We Think It's Headed, online magazine December 2021, last viewed September 22, 2022, https://www.thedrive.com/tech/43978/toyota-has-a-new-ev-strategy-heres-where-we-think-its-headed

32 Automotive News Europe (2022), Toyota may increase output of bZ4X, its first mass-market EV, last viewed November 2, 2022, https://europe.autonews.com/automakers/toyota-may-increase-output-its-first-mass-market-ev

33 InsideEV (2022), US: Hyundai Motor Group "Breaks From BEV Pack" In Q1 2022, online magazine March 2022, last viewed September 22, 2022, https://insideevs.com/news/586090/us-electric-car-sales-hyundai-2022q1/

34 InsideEV (2022c), Hyundai Announces Accelerated Electrification Strategy, online magazine March 2022, last viewed September 22, 2022, https://insideevs.com/news/571125/hyundai-accelerated-electrification-strategy/

35 ElecTrek (2022), Kia's turn: Hyundai's counterpart expects 14 BEV models by 2027 including two pickup trucks and plans to be #1 purpose-built vehicle provider by 2030, online magazine March 2022, last viewed September 22, 2022, https://electrek.co/2022/03/03/kia-turn-hyundais-counterpart-expects-14-bev-models-by-2027-plans-to-be-1-global-purpose-built-vehicle-provider-by-2030/

36 Forbes (2020), Why Hydrogen Will Never Be The Future Of Electric Cars, online magazine July 2022, last viewed September 22, 2022, https://www.forbes.com/sites/jamesmorris/2020/07/04/why-hydrogen-will-never-be-the-future-of-electric-cars/

General Motors

Projections for GM are by far the best due to its announcement to sell only zero-emission cars globally by 2035. This is the fastest transition from ICE to full BEV production among the companies analyzed. GM has developed its own "Ultium" BEV architecture[37] and invested in battery factories together with LG Chem. A wide range of BEV models has been announced, too.[38] Things are already moving fast in China: With its Chinese joint ventures, GM achieved significant EV shares in their sales in 2021. However, this was largely thanks to the success of one vehicle, the extremely small Hongguang Mini EV, which sold 420,000 units in China alone.[39] Given that GM currently offers only four BEV models and only sold around 25,000 BEVs in its US home market in 2021,[40] its plan is by far the most ambitious. However, based on the projections above, GM will still exceed the 1.5°C-compatible number of ICE LDV sales at least by 6 to 21 million or 25 % to 90%.

Due to the lack of speed in the transition to BEVs, all the automakers analyzed face considerable business and financial risks, ranging from loss of market share to new all-electric entrants to stranded assets, for example, ICE platforms currently under development on whose basis not enough vehicles can be produced to recuperate high development costs.

4.3 The ICE bubble and its potential consequences for financial markets

The gap between automakers' current planning and what is required to limit global warming to 1.5°C also presents a considerable risk to financial investors. After all, assets issued by the auto industry are a major factor in international financial markets. The relevance of the largest auto manufacturers might be slightly less apparent with regard to their stock valuations but becomes more evident in the credit and bond markets. Table 18 shows Bloomberg data on market capitalisation and outstanding debt in 2021 for the twelve largest auto manufacturers by sales volume. According to Bloomberg, Toyota, in 2021 the world's largest auto manufacturer by sales, had the highest market capitalisation – US$218 billion – among the companies analyzed. With US$239 billion, Volkswagen was the manufacturer with

37 Motortrend (2022) GM's Ultium Electric Car Platform Technology: Everything You Need to Know, online magazine March 2022, last viewed September 22, 2022, https://www.motortrend.com/news/gm-ultium-platform-technology-explained/

38 Motortrend (2022) Keeping Up with GM EV News Is Like Drinking from a Firehose. online magazine February 2022, last viewed September 22, 2022, https://www.motortrend.com/news/general-motors-2021-earnings-ev-product-news/

39 Nikkei Asia (2022) GM looks to catch Tesla in China with new low-cost EV, online magazine April 2022, last viewed September 22, 2022 https://asia.nikkei.com/Business/Automobiles/GM-looks-to-catch-Tesla-in-China-with-new-low-cost-EV

40 GM (2022), U.S. GM Sales Down 43 Percent To 440,745 Units In Fourth Quarter 2021, GM Authority online magazine March 2022, last viewed September 22, 2022, https://gmauthority.com/blog/2022/01/gm-sales-figures-numbers-results-united-states-q4-2021/

the highest outstanding debt. The market cap of the four automakers analyzed in the study was about US$470 billion in 2021, and the outstanding debt was US$671 billion. The market cap of the 12 largest auto manufacturers amounted to US$849 billion in 2021, and the outstanding debt well exceeded the trillion threshold at US$1,269 billion.

Table 18:
Capital market relevance of the 12 largest auto manufacturers (by sales) in 2021

Auto manufacturer	Market cap, billion US$	Total debt,* billion US$ * Short and long term	Cut-off date in 2021
Toyota	**218**	**231**	**31.03**
Volkswagen	**128**	**239**	**31.12**
GM	**88**	**110**	**31.12**
Ford	83	139	31.12
Mercedes Benz Group (Daimler)	82	150	31.12
BMW	67	116	31.12
Stellantis	52	36	31.12
Hyundai/Kia	**35**	**91**	**31.12**
Nissan	22	59	31.03
Suzuki	22	7	31.03
Honda	52	73	31.03
Renault	10	18	31.12
Sum Toyota, VW, GM, Hyundai/Kia	**469**	**671**	
Sum all	**859**	**1269**	

For comparison: With a sales volume of not even one-tenth of Toyota's, all-electric competitor Tesla achieved a market cap of US$1,091 billion – more than the twelve largest automakers combined – with an outstanding debt of US$9 billion.[41] This indicates that a re-evaluation of automakers given the necessary transition to electric vehicles is already underway on the stock market. However, if the ICE bubble bursts, automakers' stranded assets and financial problems will potentially significantly affect global financial markets. Potential losses could add up to more than US$2 trillion globally or even higher if automotive suppliers are also considered. Hence, not only auto industry executives but also bankers and investors should take the risk of a bursting ICE bubble seriously and mitigate it by using their influence to accelerate auto manufacturers' transition to electric vehicles. Policymakers and regulators must also address these underlying transition risks. Given the size of potentially stranded assets, it is reasonable to assume that systemic risks might arise for the financial system and the economy as a whole.

41 Data retrieved from Bloomberg. Cut-off date is 31.12.2021 apart from Japanese companies Toyota, Nissan and Honda where the fiscal year ended on 31.3.2021

Car traffic in the city of Seoul, South Korea, 2018.

5 Conclusion

In this analysis, we defined the number of LDVs with an internal combustion engine that may still be sold within a 1.5°C carbon trajectory. Comparing auto manufacturers' sales plans against this number, we further identified a significant ICE bubble – the number of ICE vehicles whose production is planned, but that cannot be sold if a 1.5°C-compatible carbon budget is not to be exceeded.

The Intergovernmental Panel on Climate Change (IPCC) identified the global carbon budget to limit warming to 1.5˚C with a 67% likelihood as 400 $GtCO_2$ between 2020 and 2050 (IPCC AR6, 2021)[42]. To remain within this budget, a phase-out of internal combustion engines for road vehicles is essential and without alternative. Considering the use of fossil fuels in other sectors of the economy, this results in a CO_2 budget of around 53 $GtCO_2$ for LDVs. Based on current fuel efficiencies and usage patterns, 315 million LDVs with fossil fuel-based internal combustion engines may still be manufactured and sold before their production needs to be phased out. To decarbonize road transport by 2050, and considering the limited number of ICE vehicles that can still be sold, automakers need to phase out the production of ICE LDVs by 2030. Total decarbonization of the existing LDV fleet will take an additional 20 years due to the remaining lifespan of ICE vehicles sold until 2030.

The exact number of remaining ICE vehicle sales depends on fuel efficiency, annual kilometres driven, and the vehicle's actual lifespan or usage or both. However, even with significant improvement in fuel efficiencies, a phase-out of ICE vehicles is required to remain within the carbon budget and achieve zero CO_2 emissions by 2050.

Furthermore, a shift from individual transport systems such as passenger vehicles to public transport and non-energy mobility, such as cycling and walking, is essential and would reduce the required number of new BEVs.

Finally, the early retirement of ICE vehicles between 2030 and 2050 would lead to a further CO_2 reduction. This analysis assumes a vehicle lifespan of 15 to 20 years, resulting in cumulative global CO_2 emissions between 2031 and 2050 of 17.8 $GtCO_2$ – about 34% of the total carbon budget for LDVs.
The analysis of expected global sales for ICE cars projected based on the business plans of four of the world's largest auto manufacturers, VW, Toyota, Hyundai/Kia, and GM, clearly shows that established auto companies aim to produce significantly more ICE vehicles than possible under a 1.5˚C-compliant

42 IPCC (2021), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change, Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.). Cambridge University Press.

trajectory. The calculated number of ICE vehicles current plans of the four leading automakers foresee manufacturing would be twice as high and therefore incompatible with the Paris Climate Agreement.

Given the mismatch between current plans and the needs of the Paris Agreement, manufacturers must accelerate the move to increase their BEV sales. Only an ambitious transition to 100 percent BEV sales by 2030 will ensure compliance with a 1.5°C-compatible carbon budget. Phasing out the internal combustion engine by 2030 is even more important, considering that the calculations and projections do not include any growth in annual sales beyond pre-pandemic levels. If auto manufacturers wanted to expand the market, an even earlier ICE phase-out would be necessary to stay within the carbon budget.

The ICE bubble – the 330 to 463 million ICE vehicles manufacturers plan to produce but that exceed the number of 315 million possible ICE LDV sales under a 1.5°C aligned carbon budget – poses significant business and financial risks for each of the automakers. These include stranded assets, such as the new ICE platforms currently under development that will produce models that manufacturers can no longer sell. In addition to sunk costs, established automakers face an even more significant threat: the loss of market share to new all-electric market entrants like Tesla. Risks also extend to investors and financial markets. With over US$1.2 trillion in outstanding debt and a market capitalisation of US$859 billion among the twelve largest auto manufacturers alone, over US$2 trillion are at risk globally – even more if automotive suppliers are also considered. More detailed research is needed to assess and quantify these financial risks in detail.

To meet the 1.5°C goal, leading automakers must transition to 100 percent BEV sales by 2030. This must go hand in hand with expanding the required charging infrastructure and generating renewable electricity to charge EV batteries. Securing scarce raw materials for battery production sustainably is an additional challenge. Therefore, automakers must focus on the entire value chain of electromobility, which can have a positive mid- and long-term effect on company value.

Appendix

The role of decarbonization in the electricity sector

The advantage for battery electric vehicles in regard to their CO_2 emissions assumes that the electricity consumed is generated with decreasing specific CO_2 emission per kilowatt-hour. In this analysis, the specific CO_2 emission for electricity generation and the variation between 2020 and 2050 is based on the 1.5˚C One Earth Climate Model (OECM) scenario (Teske et al., 2019). In the OECM, fossil fuel-based electricity generation will be phased out globally by 2050 and replaced entirely by renewable power plants. Table 19 shows the electricity generation shares by technology between 2020 and 2050.

Table 19:
Global electricity supply shares under the OECM 1.5 °C pathway

		2019	2025	2030	2035	2040	2050
Coal	[%]	31%	17%	5%	1%	0%	0%
Lignite	[%]	7%	1%	1%	1%	0%	0%
Gas	[%]	24%	20%	15%	8%	4%	0%
Oil	[%]	3%	2%	1%	0%	0%	0%
Nuclear	[%]	10%	7%	4%	2%	0%	0%
Hydrogen*	[%]	0%	0%	0%	2%	2%	5%
Hydro power	[%]	16%	14%	13%	10%	9%	9%
Wind	[%]	5%	14%	22%	28%	32%	36%
Solar photovoltaic	[%]	2%	18%	30%	37%	36%	34%
Biomass	[%]	1%	3%	2%	2%	1%	1%
Geothermal	[%]	0%	1%	2%	2%	3%	3%
Solar thermal power plants	[%]	0%	1%	4%	8%	10%	10%
Ocean energy	[%]	0%	0%	0%	1%	1%	1%
Renewables share	[%]	25%	52%	74%	89%	95%	100%
Electricity supply: Specific CO_2 emissions per kWh	[gCO_2/kWh]	509	290	136	53	24	0

(*) Hydrogen produced with 100% renewable electricity

Furthermore, due to the electrification of the transport sector, global electricity demand from transport will increase from around 400 TWh per year in 2020 to around 5,000 TWh by 2040 and remain at that level for the following years. To decarbonize the road transport sector, the electricity sector must be decarbonized simultaneously, and additional electricity demand must be generated entirely by renewable power plants.

Cars destroyed by the French Fire, during California's 2021 record fire season. Climate change, fuelled in part by transport emissions, is increasing the frequency and severity of wildfires not only in California but also all over the world.