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Net Zero: The Remaining Global Market Volume for Internal Combustion Engines in Light-Duty Vehicles under a 1.5 °C Carbon Budget Trajectory

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Abstract: To achieve the goals of the Paris Climate Agreement, decarbonization targets for the global automotive industry are required. We assess the quantity of light-duty vehicles (LDVs) with internal combustion engines (ICEs) that can be manufactured within the identified carbon budget and compare it with the current sales plans of the four largest automobile manufacturers—Volkswagen, General Motors, Toyota, and Hyundai/Kia—as representative of traditional car manufacturers. We first describe the quantification of a carbon budget for LDVs under the 1.5 °C target and a methodology for calculating the market shares that will allow different drive-train technologies to stay within it. The global LDV market for new sales and historic and future vehicle retirement rates are presented, together with assumptions for car usage (in passenger kilometres per year) and fuel efficiencies. We calculate the quantity of ICE LDVs that can be sold before the manufacture of ICEs must cease globally. We then compare this upper global limit with the current sales plans of car companies. The plans of the four manufacturers differ, but all considerably exceed the number of ICE vehicle sales required to meet the 1.5 °C target. This analysis does not forecast the development of the global LDV market, but assesses the gap between manufacturers' intention and the requirement under a 1.5 °C pathway.

Keywords: 1.5 °C pathway; internal combustion engine (ICE); battery electric vehicle (BEV); car industry sector; decarbonization; Volkswagen; Toyota; General Motors (GM); Hyundai

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1. Introduction

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 (...)'. The Intergovernmental Panel on Climate Change (IPCC) further quantified the carbon budget required to achieve this target in its Sixth Assessment Report of the Working Group (IPCC, 2021). According to the IPCC, a global carbon budget of 400 $GtCO_2$ is required to limit the temperature rise to 1.5 °C (with 67% likelihood) by 2050.

With current global annual energy-related CO_2 emissions, this carbon budget would be exhausted within a decade. This raises the question of the remaining carbon budgets for specific industries and end-use sectors. The decarbonisation of road transport and in particular of passenger vehicles plays an important role in complying with the Paris Climate Agreement.

The European Union agreed to effectively ban new cars with internal combustion engines by 2035 as part of the '*Fit for 55 package*' (EU 2022) [1]. However, how many cars with internal combustion engines can still be produced and sold globally without exceeding the defined carbon budget? Are the plans of the main car manufacturers' in line with the required decarbonization?

In this analysis, we compare the global carbon budget for light-duty vehicles (LDVs) [2] with internal combustion engines (ICEs), of around 50–55 $GtCO_2$ (Teske et al., 2022) [3], with the published plans of the four main car manufacturers (as of May 2022).

The analysis is divided into three parts. In the first section of the study, we calculate how many LDVs—cars and vans—with ICEs can still be sold worldwide before the global CO_2 budget limiting the temperature increase to a maximum of 1.5 °C is exhausted. The current and future trajectories for LDV sales are broken down into five drive-train technologies with four different engine sizes. The aim of this part of the study 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 automobile sector. The analysis concludes with the quantity of ICE vehicles that can be sold before the manufacture of ICEs must cease globally.

In the second section, the future sales plans for ICEs and BEVs of the four largest car manufacturers—Toyota, Volkswagen, Hyundai/Kia, and General Motors—which currently cover 40% of the global market, are analysed, and the permitted global sales of ICE vehicles until 2040 is calculated under three scenarios.

In the third section, we compare the calculated ICE sales consistent with a 1.5 °C carbon budget with the plans of the four car manufactures, including an estimate of the global ICE sales permitted for all other manufacturers.

2. Deriving the Remaining Global Market Volume for ICEs for LDVs under a 1.5 °C Carbon Budget Trajectory

The remaining global carbon budget for LDVs is based on the One Earth Climate Model (OECM)—a global 1.5 °C pathway that includes all industry sectors and the overall energy industry. The OECM is an integrated assessment model for climate and energy pathways that focuses on 1.5 °C scenarios (Teske et al. 2022 [3]). In this study, we examined the current and future trajectories for LDV sales, broken down into five drive-train technologies with four different engine sizes.

2.1. Global Car Market in 2020–2021

The global car market has grown by 2.8% per year, on average, since 2005. Only during the global financial crises in 2008 and 2009 and at the beginning of the COVID pandemic did the car market decrease, by around 5%. However, sales jumped back in both cases in the following year. Therefore, the market did not actually decrease, but car purchases were merely postponed. The regional annual markets for LDVs in the USA and the European Union have been relatively constant since 2005, with the same volumes of around 15.5 million car sales each per year (OICA 2021) [4]. The Japanese market has shown a slight downward trend, from 4.3 million cars in 2005 to 3.5 million cars per year since 2015. The main growth is in China, where the annual car sales have increased by a factor of five since 2005—from 5 million to 25 million in 2019 (Figure 1).

The global market for LDVs is dominated by vehicles with ICEs. Table 1 shows that about 99% of all new cars sold in 2019 had ICE drive trains and only 0.5% were electric vehicles. The market share for battery-powered electric vehicles (BEVs) increased significantly to just under 6% in 2021 (BNEF 2021) (BNEF (2021), Global EV Sales on Track to Hit Record 6.3 Million in 2021). The dominant engine size for passenger vehicles in 2019 and 2020 was 101–200 kW (45%), followed by the 50–100 kW class (31%).

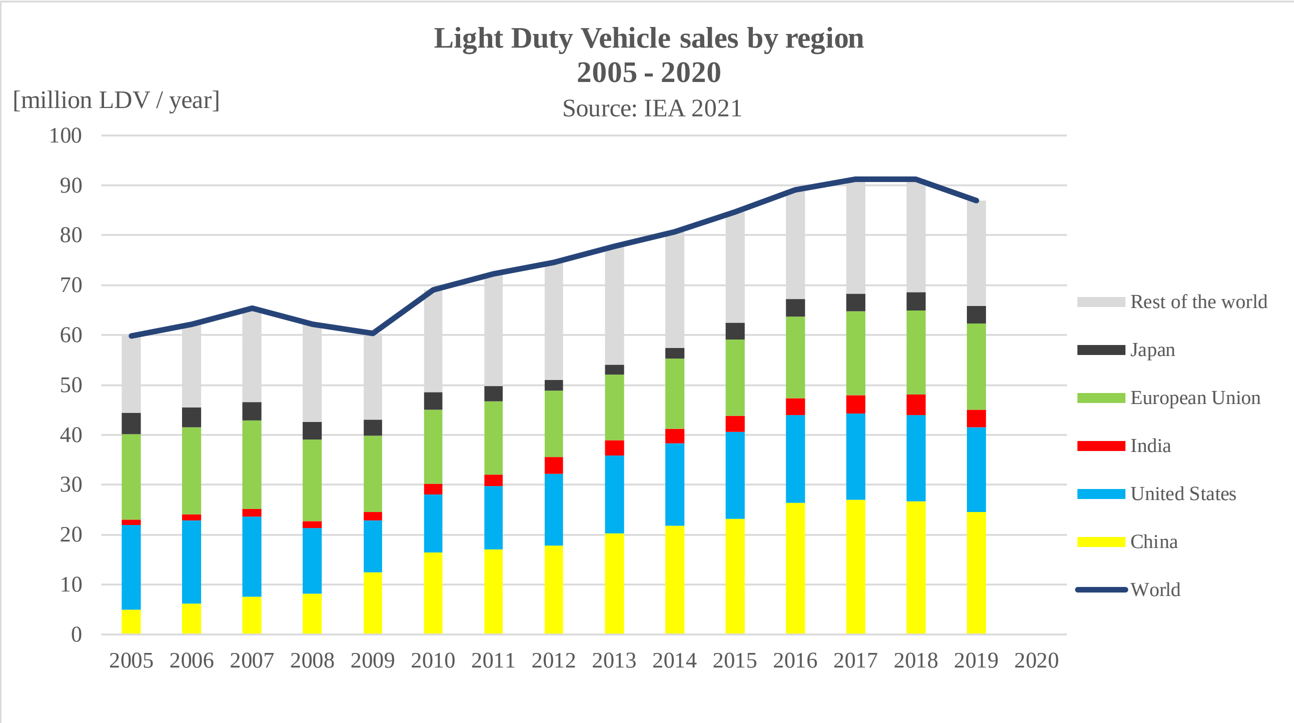


Figure 1. Light-duty vehicle sales by region in 2005–2020.

Table 1. Global LDV market by drive-train technology in 2019 and market shares of four car manufacturers (CAM 2021) [5].

				Number of Produced Cars	Volkswagen	Toyota	Hyundai	GM
Engine Type		**Power Class**	**Market Share by Engine—Based on Four Manufacturers**		**VW, Audi, Skoda, Seat, Porsche**	**Toyota, Lexus**	**Hyundai, Kia, Genesis**	**Chevrolet, GMC, Cadillac, Buick**
Petrol (incl. HEV)	Petrol	<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	>200 kW	14.38%	5,214,945	812,926	2,439,915	187,478	1,774,625
Diesel	Diesel	<50 kW	0.00%	1	0	0	1	0
	Diesel	50–100 kW	4.04%	1,465,217	674,954	4682	785,581	0
	Diesel	101–200 kW	3.27%	1,187,144	975,351	14,851	189,522	7420
	Diesel	>200 kW	0.53%	192,661	69,878	0	1	122,782
PHEV (petrol/diesel)	PHEV	<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	8809	2138	17,614	4915
	PHEV	>200 kW	0.03%	11,152	11,127	0	0	25
BEV	BEV	<50 kW	0.05%	18,480	161	0	18,319	0
	BEV	50–100 kW	0.11%	38,656	29,514	0	5800	3342
	BEV	101–200 kW	0.13%	48,481	13,509	3055	15,604	16,313
	BEV	>200 kW	0.02%	8065	8065	0	0	0
Fuel Cell	FCEV	>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%	1994	0	1702	292	0
	FCEV	<200 kW	0.00%	0	0	0	0	0
Other (LPG, CNG, ethanol, etc.)	Other	>50 kW	0.01%	3286	34	0	3252	0
	Other	50–100 kW	0.17%	60,833	55,938	0	4895	0
	Other	101–200 kW	0.00%	1121	1117	0	4	0
	Other	<200 kW	0.00%	1	0	0	0	1
Total internal combustion engines			99.47%		10,714,000	10,551,121	7,294,528	7,717,930
Total electric: BEV + PHEV + Fuel Cell			0.53%		36,277,579			
Total			100.00%		Global sales:		86,892,329	

2.2. Carbon Budget

The global carbon budget is the total amount of energy-related CO_2 emissions permitted if global warming is to be limited to a maximum of 1.5 °C, with no/low overshoot. The IPCC is the United Nations body that assesses the science related to climate change. In August 2021, the IPCC published a new report that identified the global carbon budget required to achieve 1.5 °C global warming, with 67% likelihood, as 400 $GtCO_2$ between 2020 and 2050 (IPCC AR6, 2021) [6].

The UTS OECM is an integrated energy assessment model used to develop net-zero targets based on science for all major industries in a granularity and with the key performance indicators required to make short-, mid-, and long-term investment decisions (Teske et al., 2020, 2022) [7,8]. 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 take negative emissions into account, but only natural carbon sinks, such as forests, mangroves, or seaweed, to compensate for process emissions that are currently unavoidable, such as those from cement production. The OECM uses this overall remaining carbon budget to develop energy scenarios and emission pathways across all major industry sectors, buildings, and transport, and subdivides those large sectors further into specific industries.

The OECM remains within an energy-related carbon budget of 400 $GtCO_2$, whereas the recently released Net-Zero scenario of the International Energy Agency (IEA NZ 2021) [9] leads to "(...) cumulative energy-related and industrial process CO_2 emissions between 2020 and 2050 of 460 $GtCO_2$". In August 2021, the IPCC identified the global carbon budget required to achieve 1.5 °C warming (with 67% likelihood) as 400 $GtCO_2$ and that required to achieve it with 50% likelihood as 500 $GtCO_2$ between 2020 and 2050 (IPCC AR6, 2021. Another key distinction between OECM and IEA NZ is that because IEA NZ includes the use of technical measures to remove CO_2 after emissions, it is classified as an IPCC SSP2 scenario. Figure 2 shows the subsector shares of the global carbon budget in percentages and Table 2 the remaining cumulative CO_2 emissions in gigatonnes for various industries.

The 1.5 °C carbon budget for LDVs is based on the OECM global scenario results. According to this analysis (Teske et al., 2022) [10], the remaining carbon budget for road transport services between 2020 and 2050 is 68 $GtCO_2$. About 75% of road vehicles are LDVs, and the remaining 25% are commercial and freight vehicles. Therefore, it is assumed that 75% of the global carbon budget for road transport can be assigned to LDVs. Based on this assumption, 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) [11] calculated carbon budgets 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 of 50–55 $GtCO_2$ because the calculation of specific vehicle numbers with a wide range of engine types and usages involves variations in the fuel consumption per vehicle. Therefore, the calculated carbon budget includes uncertainty. Furthermore, the carbon budget for other sectors, such as for buildings or the chemical industry, are limited as well and a delayed transition to decarbonized energy supply has a knock-on effect. Hence, the carbon budget for the transport sector might even be smaller under the assumption that the global 400 $GtCO_2$ emission limit cannot exceeded.

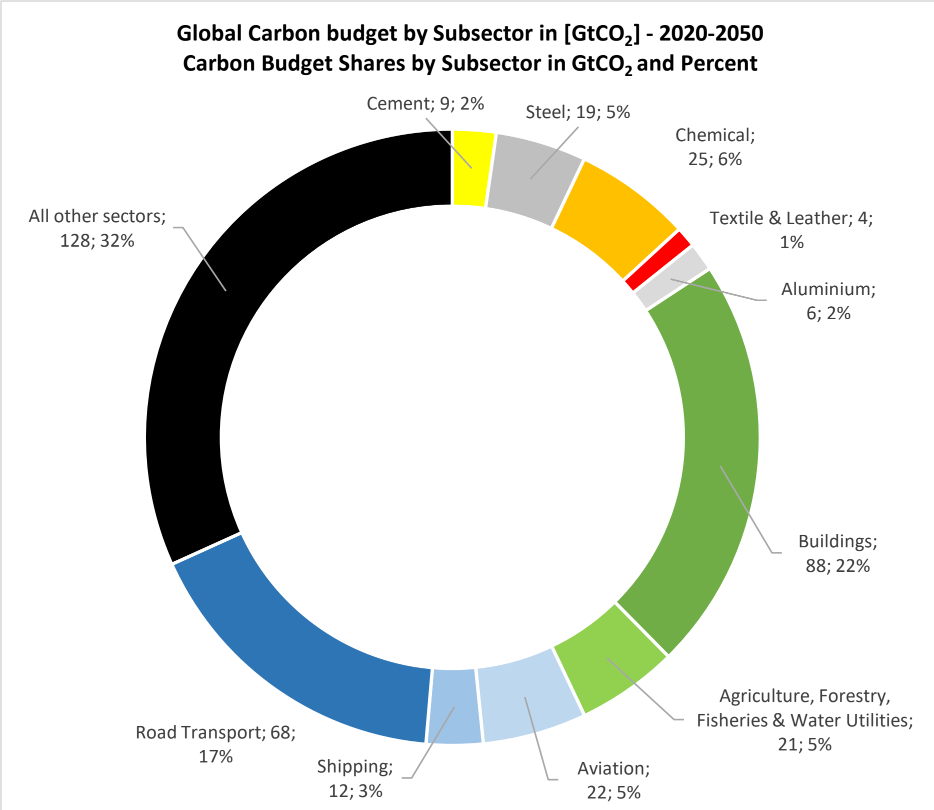


Figure 2. Global carbon budgets—total carbon budgets in $GtCO_2$ and percentages by industry sector.

Table 2. Global carbon budgets—cumulative energy-related CO_2 by industry sector.

Global Carbon Budget for Energy-Related CO_2 Emissions by Subsector (2020–2050) Total 400 $GtCO_2$ for 1.5 °C Warming (67% Likelihood)	**2020–2030 [GtCO2]**	**2020–2050 [GtCO2]**
Cement (process heat, fuels, and electricity)	6	9
Steel (process heat, fuels, and electricity)	14	19
Chemical Industry (process heat, fuels, and electricity)	17	25
Textile and Leather (process heat, fuels, and electricity)	3	4
Aluminium (process heat, fuels, and electricity)	5	6
Buildings –commercial and residential, including construction (heat, fuels, and electricity)	69	88
Fisheries (fuels and electricity)	0	1
Agriculture and Food Processing (heat, fuels, and electricity)	10	14
Forestry and Wood (heat, fuels, and electricity)	4	5
Water Utilities (heat, fuels, and electricity)	1	1
Aviation–Transport Services	15	20
Aviation Industry Direct (fuels and electricity)	0	0
Navigation–Transport Services	8	13
Navigation Industry Direct (fuels and electricity)	0	0
Road Transport–Transport Services	63	80
Road Transport Industry Direct (fuels and electricity)	2	2
Energy Industry–Production of Fossil Fuels	47	84
Remaining Energy Services (Fossil Fuels)	4	5
Utilities (Power and Gas)–Distribution	9	15
Remaining Electricity Services	1	1
Other Conversions and Losses	7	9
Total Cumulative Energy-related CO_2 Emissions	285	400

2.3. Methodology

The aim of this section of the study was to calculate how many cars with ICEs can still be sold worldwide before the global CO_2 budget required to limit the global temperature increase to a maximum of 1.5 °C is exhausted. Therefore, we do not to forecast the possible development of the global LDV market but develop a 1.5 °C-compliant benchmark for sales in the automotive industry sector.

To calculate the global CO_2 emissions from new and existing LDVs involves the following factors:

- Specific energy demand per kilometre of the car model in joules per kilometre;
- Average annual kilometres driven;
- Energy source (patrol, diesel, electricity, etc.);
- Emission intensity per unit of energy (for details see Appendix A).

Based on these parameters, the specific CO_2 emissions per kilometre driven can be calculated for each car model. This value is multiplied by the overall kilometres driven per year to give the total annual CO_2 emissions per vehicle. The emissions over the whole lifetime of the LDV must also be considered because a manufactured car with a specific emission standard per kilometre will emit CO_2 over the entire lifetime of the vehicle. The kilometres driven per year is multiplied by the average specific CO_2 emissions per kilometres and the lifetime in years.

Example: The average new LDV registered in the European Union in 2020 emitted 108.2 g of CO_2 per km (ACEA 2021a) [12], and the current average technical life time of a vehicle is 18.1 years in Western Europe (Held 2020) [13]. In 2020, the average distance travelled per car per year was assumed to be 15,000 km. This assumption is based on European data, which suggest that the average annual distance travelled per car is 18,000 km in Western Europe (Marrero et.al., 2019) [14], 20,200 km in the USA (Statista 2021) [15], and 12,100 km in Australia (ABS 2020) [16]. Based on these data, each new car sold in the European Union emits 24.3 tCO_2 over its lifespan of 15 years. To capture the effects of changing vehicle technologies and the fuels used, or the transition towards electric vehicles (EVs), in terms of the total CO_2 emissions over time (both annually and cumulatively), a highly technical resolution of the calculation method is required. Table 3 provides an overview of the calculation used for this analysis.

Table 3. Overview of the calculation method.

		Calibration with Historical Data		Projections			
		2005–2020		2020–2025	2026–2030	2031–2050	
			Data source/calculation method	Near-term	Mid-term	Long-term	Data source/calculation method
Market							
Total car stock	[1]	Statistics	IEA/CAM	Calculated	Calculated	Calculated	
Annual deviation in total car stock	[%/yr]	Calculated	Deviation relative to previous year	Input	Input	Input	
Annual car sales	[1]	Statistics	CAM	Input	Input	Input	
Cars retired annually	[1]	Calculated	Annual vehicle stock increase versus annual car	Calculated	Calculated	Calculated	
Annual retirement share	[%]	Calculated	retirement rate base on vehicle stock	Input	Input	Input	
Technology							
Drive-train market: Annual sales							
ICE–petrol	[1]	Statistics	CAM	Calculated	Calculated	Calculated	
ICE–diesel	[1]	Statistics	CAM	Calculated	Calculated	Calculated	
ICE–other fuels (ethanol, methanol, natural gas, biofuels)	[1]	Statistics	CAM	Calculated	Calculated	Calculated	Calculated with market shares (see below)

Table 3. *Cont.*

		Calibration with Historical Data		**Projections**			
		2005–2020		**2020–2025**	**2026–2030**	**2031–2050**	
Plug-in Hybrid/Hybrid (PHEV)	[1]	Statistics	CAM	Calculated	Calculated	Calculated	
Battery Electric Vehicle (BEV)	[1]	Statistics	CAM	Calculated	Calculated	Calculated	
Fuel Cell/retirement	[1]	Statistics	CAM	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	car 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]	Calculated	Market shares calculated	Input	Input	Input	and annual deviation
Battery Electric Vehicle (BEV)	[%/yr]	Calculated	based on total annual car 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							
<50	[kW]	Calculated	Calculated from	Input	Input	Input	Market share input based on
50–100	[kW]	Calculated	actual sales	Input	Input	Input	market shares of previous year
101–200	[kW]	Calculated		Input	Input	Input	and annual deviation, with X% increase/decrease
>200	[kW]	Calculated		Input	Input	Input	—different growth rates for near/mid/long-term
			Fuel Efficiency and Emissions				
		Internal Combustion Engines (petrol, diesel, hybrids, other fuels)					
Average Fuel Consumption, by technology and engine power	[l/100 km]	Statistics	CAM	Input	Input	Input	Fuel consumption in base year × efficiency factor
Fuel Emission Factors	[kgCO_2/litre]	Statistics	UBA			Constant	
Average Emissions, per kilometre	[gCO_2/km	Calculated with factors (see above) for each technology and engine power class					
		Electric Drives (PHEV, BEV, H_2)					
Average Electricity Consumption, by technology and engine power	[kWh/100 km]	Statistics	CAM	Input	Input	Input	Electricity consumption in base year × efficiency factor
Emission Intensity of Electricity Generation		Electricity generation to supply required electricity either directly to BEV or to produce H_2, according to OECM 1.5 °C scenario					
Transport Service							
Total annual passenger kilometres	[million pkm/yr]	Statistics	OECD– International Transport Forum	Calculated	Calculated	Calculated	Passenger kilometres previous year, X% increase/decrease
Annual deviation in total passenger kilometres	[%/yr]	Calculated	Deviation relative to previous year	Input	Input	Input	
Average annual kilometres per LDV	[km/car year]	Statistics	CAM	Calculated	Calculated	Calculated	
Average passengers per car	[1]	Calculated		Input	Input	Input	Assumed passenger occupancy per car

The LDV market is broken down into six different drive-train 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 cars

Each drive-train technology is subdivided into four engine classes:

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

Therefore, the overall LDV market is broken down into 24 market segments. Based on historical sales between 2005 and 2020 (IEA 2020b) [17], the market shares are calculated for each segment in terms of the total annual global car sales. For the market projection for 2021–2050, the calculation method is reversed: the market shares are input and the annual car unit numbers are calculated.

The increase in car stocks has been calculated based on the historical development of the overall car stock (OICA 2021) [18] and annual car sales (OICA 2021, IEA 2020b). The difference between the annual car sales and the actual increase in the car stock is equal to the number of cars retired every year. Based on these data, the average retirement share in the percentage of the total car stock is calculated. Again, the calculation method is reversed and the number of cars retired each year was calculated from the average long-term retirement rates.

The assumed annual retirement rate comes with a high uncertainty and the actual lifetime of ICE LDV might be longer than calculated in this analysis. To date, used cars from industrialized countries are exported to developing countries where they continue to be used for years—often as taxis or commercial vehicles. A delayed retirement of ICE LDV will reduce the global market limit for new ICE LDVs further. The calculated number of cars was distributed to the 24 segments according to the market shares 15 years ago, to reflect the average lifespan of a car. The total number of cars in each of the 24 segments was calculated—based on sales and retirements—for each year in the period 2020–2050. Furthermore, for each car segment, the energy demand, fuel demand, and resulting emissions were calculated, while considering the assumed increase in efficiency over time.

Finally, the electricity demand for all vehicles requiring electricity—either direct, such as BEV, or to produce hydrogen fuels—was calculated. The calculation of the CO_2 emissions caused during electricity generation were based on the OECM 1.5 °C power generation scenario. The OECM scenario decarbonizes electricity generation gradually from around 500 g CO_2 per kWh in 2020 to 135 g CO_2 per kWh in 2030, to achieve complete decarbonization by 2050.

The phase-out of ICE vehicles by reducing their market share—compensated by BEVs—is based on the remaining carbon budget and not on a forecast of the market for BEVs.

2.4. Assumptions for LVD Market Trajectory under 1.5 °C Warming

The assumptions used to calculate the remaining ICE car sales permitted under the Paris Climate Agreement are provided in this section. Table 4 shows the assumed global LDV sales until 2050. In 2020, the global LDV market dropped to 77.7 million cars as a result of the COVID-19 pandemic, a decline of 9 million cars compared with the previous year. However, in 2021, the market increased by 3.3 million cars, indicating a recovery in the market. In this analysis, we assume that the long-term average market will remain at the average market volume between 2005 and 2020, at around 75 million cars sold per year. The retirement rate—based on the total global vehicle stock—over the past 15 years was around 5%. Based on annual sales, the average historical retirement rate was calculated to be around 63%. For future projections, the annual retirement rate is assumed to increase to 80%, leading to a higher rate of replacement of old ICE cars with more-efficient cars and EVs.

Table 4. Projections of global annual LDV sales until 2050.

Global LDV Market	Units	2019	2020	2021	2025	2030	2040	2050
Global LDV Sales	[millions]	86,9	77.7	81.0	75.0	75.0	75.0	75.0
Retirement Rate–based on total vehicle stock	[%/yr]	5%	5%	5%	5%	5%	4%	4%
Retirement Rate–based on annual car sales	[%/yr]	63%	73%	75%	80%	80%	80%	80%

The assumed market shares by vehicle class are shown in Table 5. Battery electric vehicles (BEVs) will increase rapidly and will replace ICEs as the main market segment by 2025. It is assumed that the market shares by engine size will remain stable. Therefore, smaller city cars with engines of ≤50 kW will change from petrol and diesel to BEVs, but the overall market share of small cars will not change. Consequently, it is assumed that the average car size will not decrease, even with the introduction of electric cars. This assumption is based on observations of the car market over past years.

Table 5. Assumed market share by vehicle class in 2019–2050.

LDV Type		Units	2019	2021	2025	2030	2040	2050
Petrol	<50 kW	[%]	1.8%	1.8%	0.0%	0.0%	0.0%	0.0%
	50–100 kW	[%]	30.9%	28.3%	18.0%	0.0%	0.0%	0.0%
	101–200 kW	[%]	44.4%	41.5%	35.5%	0.0%	0.0%	0.0%
	>200 kW	[%]	14.4%	14.4%	2.4%	0.0%	0.0%	0.0%
Diesel	<50 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	50–100 kW	[%]	4.0%	2.8%	1.0%	0.0%	0.0%	0.0%
	101–200 kW	[%]	3.3%	2.1%	1.0%	0.0%	0.0%	0.0%
	>200 kW	[%]	0.5%	0.5%	0.5%	0.0%	0.0%	0.0%
PHEV/Hybrid	<50 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	50–100 kW	[%]	0.1%	1.2%	0.5%	0.0%	0.0%	0.0%
	101–200 kW	[%]	0.1%	1.2%	0.5%	0.0%	0.0%	0.0%
	>200 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
BEV–Electric	<50 kW	[%]	0.1%	0.1%	4.0%	10.0%	10.0%	10.0%
	50–100 kW	[%]	0.1%	3.0%	16.2%	40.0%	40.0%	40.0%
	101–200 kW	[%]	0.1%	2.9%	16.2%	40.0%	40.0%	40.0%
	>200 kW	[%]	0.0%	0.0%	4.0%	10.0%	10.0%	10.0%
Fuel Cell/Hydrogen	<50 kW	[%]	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%
	101–200 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	>200 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
Other (LPG/ethanol, etc.)	<50 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%
	50–100 kW	[%]	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%
	>200 kW	[%]	0.0%	0.0%	0.0%	0.0%	0.0%	0.0%

The assumed total global road transport service demand in passenger kilometres is assumed to remain at the current levels of around 42.5 billion kilometres per year—about the average demand for the past 10 years. The average number of passengers per vehicle is assumed to drop from 2.5 in 2020 to 2 in 2050 with the increased ownership of vehicles in developing countries, in which the current number of passengers per vehicle is significantly higher than in the Organisation for Economic Co-operation and Development (OECD) countries. The annual average kilometres per vehicle is assumed to decrease only slightly, from around 15,000 km in 2020 to 13,400 km in 2050. This is also an effect of increased car ownership in developing countries, and where fewer people will therefore share one vehicle (Table 6).

Table 6. Assumed development of transport demand for LDVs.

Transport Service Demand	Units	2021	2025	2030	2040	2050
Total passenger kilometres per year	[millions pkM]	43,957,632	42,652,046	42,500,000	42,500,000	42,500,000
Average annual kilometres per vehicle	[km/vehicle yr]	15,291	14,075	14,675	13,917	13,389
Average passengers per vehicle	[1]	2.5	2.5	2.25	2.125	2

The average CO_2 emissions per ICE vehicle class for the base year 2019 are shown in Table 7. It is assumed that all ICE vehicle classes have an annual increase in efficiency of 0.75% and that therefore the calculated fuel demand for new vehicles changes each year. Electric vehicles are assumed to have a slightly higher increase in efficiency (1% per year) because the technology is still in an early stage of development.

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

Average emissions of LDVs [gCO_2/km]		Units	2019
Petrol	<50 kW	[gCO_2/km]	93.2
	50–100 kW	[gCO_2/km]	128.2
	101–200 kW	[gCO_2/km]	233.0
	>200 kW	[gCO_2/km]	291.3
Diesel	<50 kW	[gCO_2/km]	94.0
	50–100 kW	[gCO_2/km]	129.2
	101–200 kW	[gCO_2/km]	235.0
	>200 kW	[gCO_2/km]	293.7
PHEV/Hybrid	<50 kW	[gCO_2/km]	93.2
	50–100 kW	[gCO_2/km]	128.2
	101–200 kW	[gCO_2/km]	233.0
	>200 kW	[gCO_2/km]	291.3
Other (LPG, ethanol, etc.)	<50 kW	[gCO_2/km]	44.6
	50–100 kW	[gCO_2/km]	61.4
	101–200 kW	[gCO_2/km]	111.6
	>200 kW	[gCO_2/km]	205.0

New vehicles, with a specific fuel/electricity demand for the year of sale, are then assumed to be in use for an average of 15 years. Table 8 shows that a petrol ICE car with 100 kW of engine power sold in 2020 is calculated to have a fuel consumption of 4.8 litre/100 km until 2035, whereas the same vehicle class sold in 2025 is assumed to have a demand of 3.3 litre/100 km until 2040 (see Table 9 for additional data).

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

Table 8. Assumed development of fuel and electricity consumption for the vehicle classes analysed.

LDVs—New Cars		Units	Efficiency Gain per Year	Average Emission in [gCO_2/km]	2020	2025	2030	2040	2050
Petrol	<50 kW	[L/100 km]	0.75%	93.2	3.6	3.5	3.3	3.1	2.9
	50–100 kW	[L/100 km]	0.75%	128.2	4.9	4.8	4.6	4.3	3.9
	101–200 kW	[L/100 km]	0.75%	233.0	9.0	8.7	8.3	7.7	7.2
	>200 kW	[L/100 km]	0.75%	291.3	11.2	10.8	10.4	9.7	9.0
Diesel	<50 kW	[L/100 km]	0.75%	94.0	3.2	3.1	3.0	2.8	2.6
	50–100 kW	[L/100 km]	0.75%	129.2	4.4	4.2	4.1	3.8	3.5
	101–200 kW	[L/100 km]	0.75%	235.0	8.0	7.7	7.4	6.9	6.4
	>200 kW	[L/100 km]	0.75%	293.7	10.0	9.6	9.3	8.6	8.0
PHEV/Hybrid	<50 kW	[L/100 km]	0.75%	93.2	3.6	3.5	3.3	3.1	2.9
	50–100 kW	[L/100 km]	0.75%	128.2	4.9	4.8	4.6	4.3	3.9
	101–200 kW	[L/100 km]	0.75%	233.0	9.0	8.7	8.3	7.7	7.2
	>200 kW	[L/100 km]	0.75%	291.3	11.2	10.8	10.4	9.7	9.0
Other: LPG/Ethanol, etc.	<50 kW	[L/100 km]	0.75%	44.6	2.4	2.4	2.3	2.1	2.0
	50–100 kW	[L/100 km]	0.75%	61.4	3.4	3.2	3.1	2.9	2.7
	101–200 kW	[L/100 km]	0.75%	111.6	6.1	5.9	5.7	5.3	4.9
	>200 kW	[L/100 km]	0.75%	205.0	11.2	10.8	10.4	9.7	9.0
CO_2/kWh Electricity–1.5 °C Scenario		[kg/kWh]			0.51	0.25	0.135	0.0265	0
BEV–Electric	<50 kW	[kWh/100 km]	1.00%		5.4	5.0	4.7	4.3	3.9
	50–100 kW	[kWh/100 km]	1.00%		11.7	10.7	10.2	9.2	8.4
	101–200 kW	[kWh/100 km]	1.00%		16.6	15.3	14.5	13.1	11.9
	>200 kW	[kWh/100 km]	1.00%		22.5	20.7	19.6	17.8	16.1
Fuel Cell/ Hydrogen	<50 kW	[kWh/100 km]	1.00%		10.8	9.9	9.4	8.5	7.7
	50–100 kW	[kWh/100 km]	1.00%		23.4	21.5	20.4	18.5	16.7
	101–200 kW	[kWh/100 km]	1.00%		33.3	30.6	29.1	26.3	23.8
	>200 kW	[kWh/100 km]	1.00%		45.0	41.3	39.3	35.5	32.1

Table 9. Emission factors per litre (UBA 2022 [19]).

Emission Factors		
Petrol	[$kgCO_2$/L]	2.33
Diesel	[$kgCO_2$/L]	2.64
LPG	[$kgCO_2$/L]	1.64

2.5. Results—LDV Market Trajectory under 1.5 °C Warming

Under the assumptions itemized in Section 2.4 and calculated with the methodology described in Section 2.4, the market for LDVs must change significantly if we are to remain within the carbon budget identified to limit the mean rise in global temperature to a maximum of 1.5 °C.

Table 10 shows the calculated global annual LDV sales by vehicle class that are possible before the carbon budget is exceeded. The limit for petrol- and diesel-fuelled ICE LVDs will be reached by 2029. Under the assumption that BEVs will replace ICE cars while the overall car market remains at around 75 million vehicles a year, the BEV market must reach the ICE manufacturing level by 2025. By 2050, a total of just over 2 billion new EVs must be produced not only to replace ICE cars in the new sales seg-ment, but also to replace old ICE vehicles at the end of their lifetimes.

Table 10. Calculated global annual car sales by vehicle class.

Annual LDV Sales		2021	2025	2030	2035	2040	2050
Petrol	<50 kW	1.46	0.00	0.00	0.00	0.00	0.00
	50–100 kW	22.95	13.50	0.00	0.00	0.00	0.00
	101–200 kW	33.61	26.63	0.00	0.00	0.00	0.00
	>200 kW	11.64	1.78	0.00	0.00	0.00	0.00
Total Petrol Engines		69.67	41.91	0.00	0.00	0.00	0.00
Diesel	<50 kW	0.00	0.00	0.00	0.00	0.00	0.00
	50–100 kW	2.30	0.75	0.00	0.00	0.00	0.00
	101–200 kW	1.70	0.75	0.00	0.00	0.00	0.00
	>200 kW	0.43	0.40	0.00	0.00	0.00	0.00
Total Diesel Engines		4.43	1.90	0.00	0.00	0.00	0.00
PHEV/Hybrid	<50 kW	0.00	0.00	0.00	0.00	0.00	0.00
	50–100 kW	0.97	0.34	0.00	0.00	0.00	0.00
	101–200 kW	0.95	0.34	0.00	0.00	0.00	0.00
	>200 kW	0.02	0.02	0.00	0.00	0.00	0.00
Total PHEV		1.95	0.70	0.00	0.00	0.00	0.00
BEV–Electric	<50 kW	0.04	3.04	7.50	7.50	7.50	7.50
	50–100 kW	2.40	12.14	30.00	30.00	30.00	30.00
	101–200 kW	2.35	12.14	30.00	30.00	30.00	30.00
	>200 kW	0.02	3.04	7.50	7.50	7.50	7.50
Total BEV	0	4.81	30.36	75.00	75.00	75.00	75.00
Fuel Cell/Hydrogen	<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
	>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.)	<50 kW	0.01	0.01	0.00	0.00	0.00	0.00
	50–100 kW	0.14	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
	>200 kW	0.00	0.00	0.00	0.00	0.00	0.00
Total Other		0.15	0.13	0.00	0.00	0.00	0.00
Total Cumulative Car Sales–starting 2021		81.00	382.24	757.10	1131.70	1507.05	2266.97
Total Annual Car Sales		81.00	75.00	75.00	75.00	75.00	75.00

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

Table 11. Global annual LDV sales versus retirement by drive-train.

Annual LDV Sales and Retirements by Technology		Units	2021	2022	2025	2030	2035	2040	2050
Petrol	Sales	[million cars/yr]	69.7	59.8	41.9	0.0	0.0	0.0	0.0
	Retirements	[million cars/yr]	−55.6	−54.2	−54.9	−54.9	−54.9	−33.7	−10.8
Diesel	Sales	[million cars/yr]	4.4	3.2	1.9	0.0	0.0	0.0	0.0
	Retirements	[million cars/yr]	−5.2	−5.1	−5.2	−5.1	−4.9	−2.3	−0.1
PHEV/Hybrid	Sales	[million cars/yr]	1.9	1.7	0.7	0.0	0.0	0.0	0.0
	Retirements	[million cars/yr]	−0.2	−0.3	−0.5	−0.4	−0.3	0.0	0.0
BEV–Electric	Sales	[million cars/yr]	4.8	10.9	31.3	75.8	75.5	76.0	85.9
	Retirements	[million cars/yr]	−0.2	−0.2	−0.2	−0.2	−0.2	−24.3	−60.0
Fuel Cell/ Hydrogen	Sales	[million cars/yr]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	retirements	[million cars/yr]	0.0	0.0	0.0	0.0	0.0	0.0	0.0
Other (LPG/ ethanol, etc.)	Sales	[million cars/yr]	0.1	0.1	0.1	0.0	0.0	0.0	0.0
	Retirements	[million cars/yr]	−0.2	−0.2	−0.2	−0.2	−0.1	0.0	0.0
Total Annual Sales		[million cars/yr]	81.0	75.7	75.7	75.9	75.8	75.5	76.0
Total Annual Retirements		[million cars/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 manufacture of 371.7 million additional vehicles (base year 2021) between 2021 and 2050, whereas for diesel cars, the limit will already be reached after 16.9 million cars (Figure 4). Therefore, to stay within a 1.5 °C-compatible carbon trajectory, a total of 388.6 million ICE cars can still be sold.

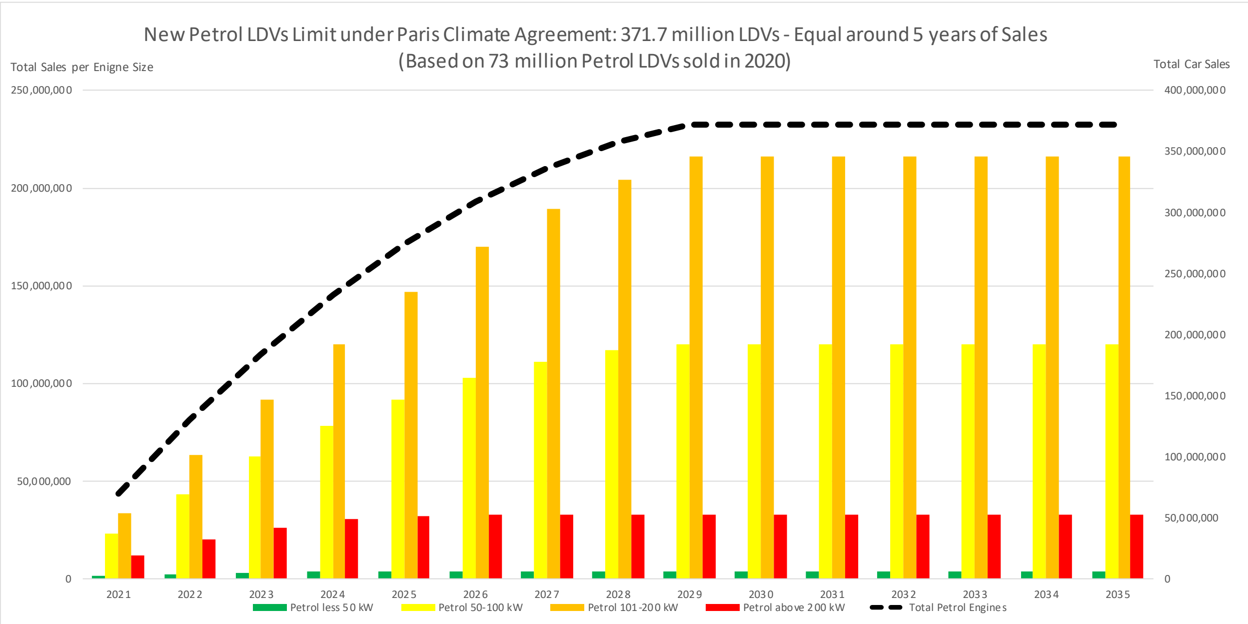


Figure 3. Global limit of new petrol cars under the Paris Climate Agreement.

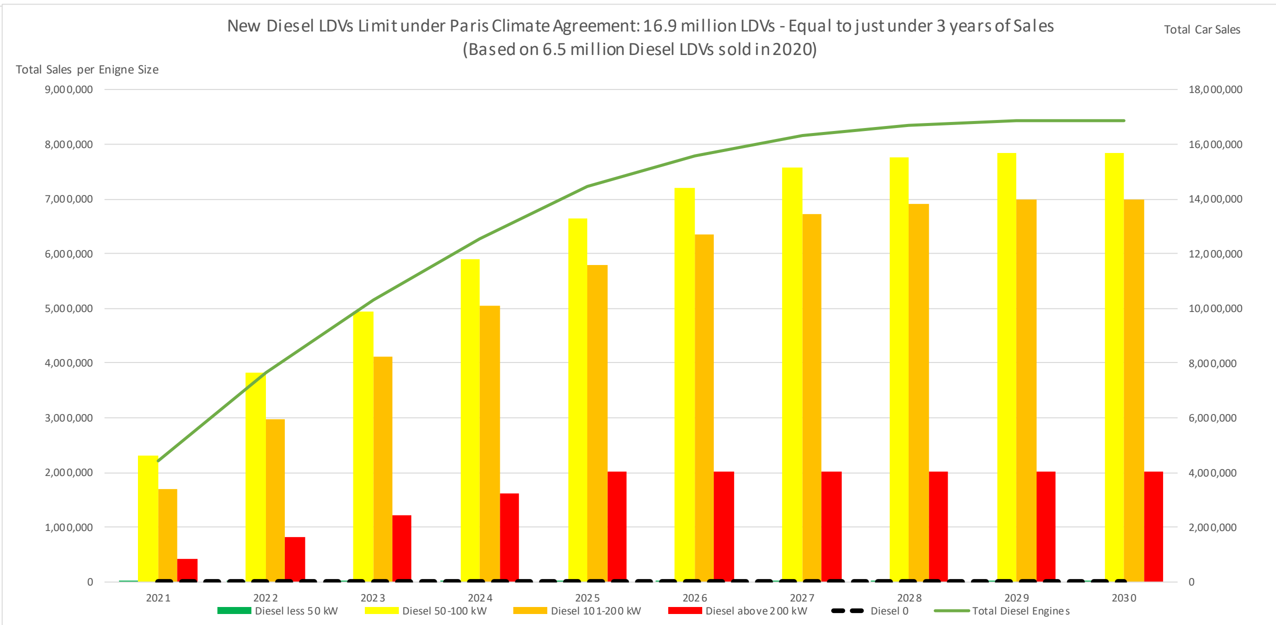


Figure 4. Global limit of new diesel cars under the Paris Climate Agreement.

The market for BEVs must increase from around 5 million vehicles in 2021 to 10.9 million in 2022—which is within the same range of the 2022 forecast by Bloomberg New Energy Finance (BNEF 2022) [20], which estimated 10.5 million BEVs for that year.

When replacing fossil-fuelled ICE cars to remain within the carbon budget, the replacement rate for existing cars must be around 80% from 2025 onwards. This high replacement rate must remain in place until 2050 to achieve the full decarbonization of the LDV fleet. Figure 5 shows the new car sales and retirements by drive train until 2050.

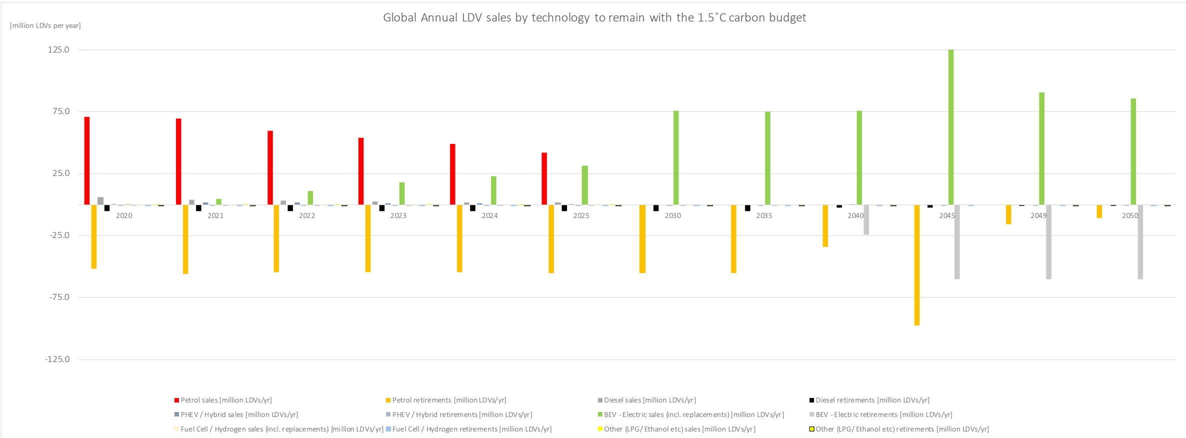


Figure 5. Global annual car sales and retirements.

Table 12 shows the global annual CO_2 emissions of the LDV fleet and the cumulative emissions for 2020–2050. About one third of all CO_2 emissions from fossil-fuelled ICE vehicles will be emitted after their production has already ceased in 2030. The replacement of ICE vehicles will be a high priority after 2030, in order to remain within the carbon budget.

Table 12. Global CO_2 emissions from LDVs by technology.

LDVs			**2021**	**2025**	**2030**	**2035**	**2040**	**2050**	**2020–2030**	**2020–2050**
CO_2/kWh Electricity–1.5 °C Scenario	0	[kg/kWh]	0.458	0.25	0.135	0.057	0.0265	0		
Petrol	<50 kW	[$MtCO_2$]	31	25	18	9	5	1	278	388
0	50–100 kW	[$MtCO_2$]	686	607	493	293	178	2	6768	10,394
0	101–200 kW	[$MtCO_2$]	1678	1526	1339	838	505	65	17,155	27,803
0	>200 kW	[$MtCO_2$]	671	550	388	202	134	1	6094	8579
Diesel	<50 kW	[$MtCO_2$]	0	0	0	0	0	0	0	0
0	50–100 kW	[$MtCO_2$]	79	53	31	7	1	0	618	711
0	101–200 kW	[$MtCO_2$]	128	104	77	41	29	2	1165	1714
0	>200 kW	[$MtCO_2$]	37	37	27	13	5	0	386	541
PHEV/Hybrid	<50 kW	[$Mt CO_2$]	0	0	0	0	0	0	0	0
0	50–100 kW	[$MtCO_2$]	18	6	1	1	0	0	77	113
0	101–200 kW	[$MtCO_2$]	32	11	2	2	0	0	138	200
0	>200 kW	[$MtCO_2$]	2	2	1	1	0	0	16	21
BEV–Electric	<50 kW	[$Mt CO_2$]	0	6	7	3	2	0	53	91
0	50–100 kW	[$MtCO_2$]	20	48	65	25	15	0	475	800
0	101–200 kW	[$MtCO_2$]	28	69	92	35	21	0	677	1140
0	>200 kW	[$MtCO_2$]	0	23	31	12	7	0	220	375
Fuel Cell/ Hydrogen	<50 kW	[$MtCO_2$]	0	0	0	0	0	0	0	0
0	50–100 kW	[$MtCO_2$]	0	0	0	0	0	0	0	0
0	101–200 kW	[$MtCO_2$]	0	0	0	0	0	0	1	1
0	>200 kW	[$MtCO_2$]	0	0	0	0	0	0	0	0
LPG and Ethanol	<50 kW	[$MtCO_2$]	0	0	0	0	0	0	1	1
0	50–100 kW	[$MtCO_2$]	2	2	1	1	0	0	20	28
0	101–200 kW	[$MtCO_2$]	0	0	0	0	0	0	1	1
0	>200 kW	[$MtCO_2$]	0	0	0	0	0	0	0	0
Total Emissions LDVs		[$MtCO_2$]	3414	3063	2560	1476	898	71	34,144	52,902

2.6. Key Results by Manufacturer

When the remaining ICE car sales that are still possible within the CO_2 budget are divided among the four car manufacturers analysed, according to their current market shares, the following results emerge.

Figure 6 shows the remaining petrol ICE car sales possible if the carbon budget is to remain within the 1.5 °C scenario, by car brand. The analysed car manufacturers VW, Toyota, Hyundai, and General Motors share about 40% of the global petrol ICE car market, with similar market sizes for each brand. Therefore, the remaining sales will be distributed equally to those car manufacturers, with an average of around 10% each. However, the results for diesel LDVs, shown in Figure 7, are significantly different. VW has by far the largest market share of diesel ICE LDVs, with one quarter of the world market. Under the assumption that the market shares for diesel cars will remain the same, VW can sell about 4.2 million additional diesel cars between 2021 and 2030, before their production must be phased-out to remain within the carbon budget.

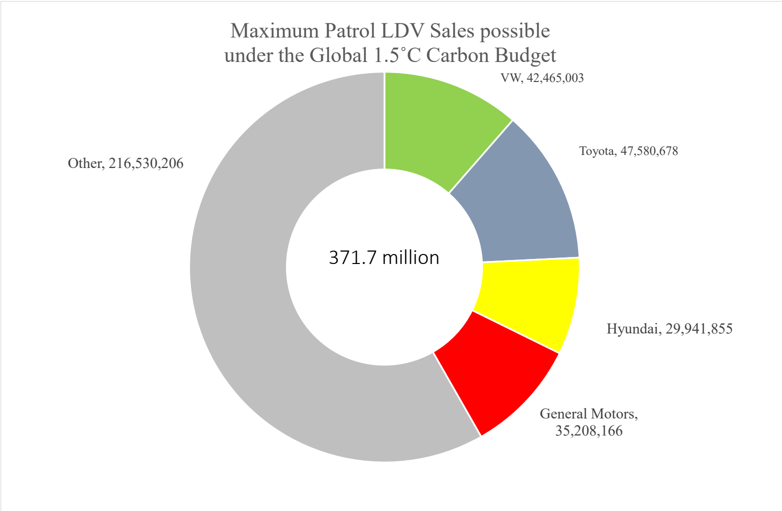


Figure 6. Remaining petrol-driven ICE LDV sales permitted, by manufacturer, if the carbon budget is to remain under 1.5 °C.

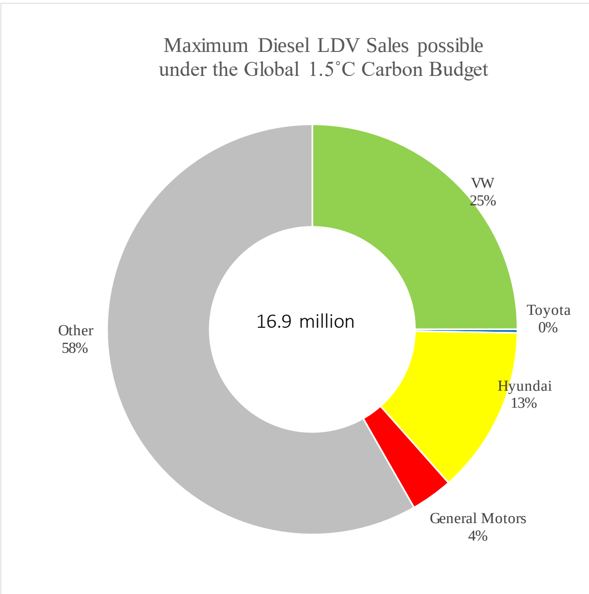


Figure 7. Remaining diesel-powered ICE LDV sales permitted, by manufacturer, if the carbon budget is to remain under 1.5 °C.

3. Deriving the Global Market Volume for ICEs for LDVs until 2050 on the Basis of Announcements by the Four Major Car Manufacturers

A 1.5 °C-compliant residual budget was calculated in the previous section, based on the sectoral CO_2 budget for the transport sector, which allows a maximum of 388,6 million LDVs with ICEs to be sold by 2030. In this section, we analyse the sales plans of four of the largest car manufacturers. The objective of the analysis is to estimate the planned sales of cars with ICEs on the basis of the announced ramp-up electromobility scenarios and to compare this result with the ICE sales that are consistent with the carbon budget, as described in the first section.

3.1. Methodology to Identify Projected Global ICE LDV Sales

Forecasting the planned ICE sales is not an easy task and depends on many factors. In addition to the planning of the original equipment manufacturers, market developments and exogenous conditions (such as the COVID-19 pandemic) play a dominant role. To ensure that the results of the following analysis are reliable, the assumptions underlying the projections of ICE sales are as conservative as possible, i.e., favour the manufacturers, so that the estimates of planned ICE sales presented should be regarded as the lower limits of car manufacturers' planned ICE sales.

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

- No further growth is assumed after the recovery of sales to pre-pandemic levels. This means that global automobile sales of LDVs will rise to 85 million vehicles by 2022, as in 2019, and ultimately remain at that level. Although GM and Asian manufacturers Toyota and Hyundai/Kia had already reached their pre-crisis level in 2021, this will not be the case for Volkswagen until at least 2022 due to supply bottlenecks for microchips.
- New market entrants and all-electric car companies, such as Tesla, are excluded from the analysis and are not examined. This modelling is based on the—hypothetical—assumption that established car companies will not lose any market share to new all-electric manufacturers.
- No downsizing: It is also assumed that manufacturers will not change the composition of their ICE model portfolios. In other words, neither will the historical trend towards heavier and more powerful vehicles continue, nor will it be reversed in favour of smaller and lighter ICE-driven vehicles.
- No biofuels or synthetic fuels: Consistent with the assumptions made for the calculation of the 1.5 °C budget for ICE cars in Section 2, there is no expansion of the use of biofuels to reduce emissions, and synthetic fuels, including hydrogen, play no 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 analysed. It is assumed 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 have been developed for each manufacturer based on the targets and plans they have published: a linear pathway and an exponential pathway based on an S-curve, and a combination of these two curves. This results in a total of 12 alternative pathways for the ramp-up of BEV production and sales. These pathways were used in the second step to approximate the global transition scenarios.
- The global ramp-up scenarios for BEVs, in combination with the assumed total global sales, allow the manufacturers' implied planned sales of ICE cars to be estimated.

- Manufacturers' announcements are used to estimate the ramp-up of BEV sales. However, manufacturers make very limited statements on their global plans, which is why we included announcements linked to specific regions for where we have no further specifications. This approach favours the car manufacturers because their commitments to more-advanced car markets are applied to all global markets. In fact, manufacturers are proclaiming the opposite—that ICE cars can and will be sold in certain less-developed regions way beyond 2040.
- Although no global phase-out dates for the internal combustion technology by 2040 have been communicated by the manufacturers examined, it is assumed that they will produce emissions-free cars from 2040 onwards. This assumption is not consistent with the manufacturers' statements because they expect to sell ICE cars in less-developed markets beyond 2040. Therefore, the transition to BEVs could also be lower than estimated, because we have extrapolated the announcements that some manufacturers have made for specific key markets, such as China, the EU, and the USA, to the entire global market, including developing countries.

3.2. Analysis of Sales Plans and 'Electric Vehicle Pledges' of the Four Major Car Manufacturers: Volkswagen, GM, Hyundai/Kia, and Toyota

Companies are adopting different approaches when communicating their transformation plans. Whereas some manufacturers disclose only a few details of their strategies and sometimes communicate very vague phase-out dates for ICEs in the distant future, other manufacturers publish detailed strategies, including numerous intermediate milestones. Only General Motors (GM) has communicated an exact global phase-out date - 2035. Hyundai/Kia refers to phasing out ICE by 2040 in "major markets". Volkswagen and Toyota have so far refused to clearly commit to entirely phasing-out ICEs (Table 13).

Table 13. Communicated ICE phase-out plans.

VW Group	Toyota	Hyundai/Kia	GM
No date *	No date	2040 **	2035

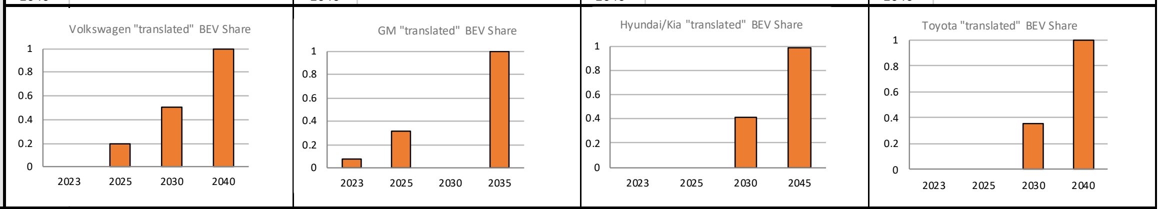
* Initially announced as 2040, but stopped communicating this date. ** For major markets".

The Volkswagen Group initially announced it would phase-out ICE cars by 2040 (Handelsblatt 2018) [21]. However, unlike Toyota, VW has committed to several intermediate steps and also intends to stop selling ICE cars in certain developed countries by 2035. Figure 8 shows the various milestones in the ramp-up of BEVs based on the plans communicated by the manufacturers. The underlying information is derived from annual reports, investor briefings, press releases, and enquiries to the manufacturers.

3.3. Estimation of ICE Vehicles Sold by the Four Major Car Manufacturers

Figure 9 shows three possible production ramp-up scenarios over time: S-curve, linear, and a combination of the two. The S-curve scenario consists of a moderate start, a steep ramp-up, and a plateau when market saturation is reached. When entering the plateau phase, only marginal cost reductions will materialize. Linear growth is determined by steady growth over time, with no steep ramp-up phase. This analysis defines the linear growth pattern as less ambitious than the S-curve pattern.

	Volkswagen		GM		Hyundai Motor Group		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	2025	*producing and selling one million BEVs in North America and China respectively*				
	2030	50% of global sales to be BEVs	2030		2030	3.07 Million BEVs by 2030 - 1.87 by Hyundai and 1.2 million by Kia	2030	*„We aim to achieve global sales of 3.5 million battery EVs per year by 2030"*
	2040	*"nearly 100% zero-emission vehicles in all major markets"*	2035	*"aspiration to eliminate tailpipe emissions from new light-duty vehicles globally by 2035"*	2040	*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		**"translated" BEV Share**		**"translated" BEV Share**		**"translated" BEV Share**		**"translated" BEV Share**
			2023	8%				
	2025	20%	2025	32%				
	2030	50%	2030		2030	41%	2030	35%
			2035	100%				
	2040*	99%	2040	100%	2040*	99%	2040*	99%
Source	https://www.volkswagenag.com/presence/investorrelation/publications/presentations/2021/07/EN-Herbert%20Diess_Speech%20NEW%20AUTO%20Strategy%20Presentation.pdf; https://www.volkswagen-newsroom.com/de/publikationen/reden/reden-jahrespressekonferenz-2021-641/download		https://www.nytimes.com/2021/01/28/business/gm-zero-emission-vehicles.html; https://media.gm.com/media/cn/zh/gm/news.detail.html/content/Pages/news/cn/zh/2022/Apr/0427-gm-q1-earnings.html		https://www.hyundaimotorgroup.com/news/CONT0000000000012239; https://press.kia.com/eu/en/home/media-resouces/press-releases/2022/Kia-CEO-Investor-Day.html		https://global.toyota/en/newsroom/corporate/36428993.html	



*No phase out date announced

Figure 8. Communicated BEV production and sales goals.

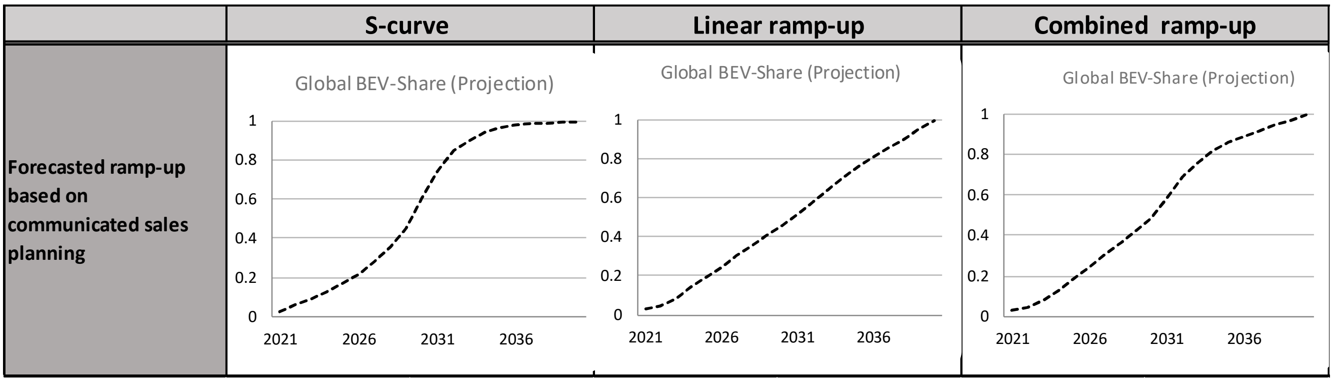


Figure 9. Three technological transition scenarios.

After the introduction of the automobile to the USA before 1938, for example, the industry showed linear growth (NBER) [22]. Both S-curve and linear markets and manufacturing growth require favourable conditions to support and maintain growth. In terms of the car industry in the past century, the expansion of the required infrastructure, such as roads, petrol stations, and technicians for maintenance, supported and enabled strong linear growth. With the introduction of BEVs, a charging infrastructure is required and is therefore a key prerequisite for linear growth. Furthermore, the ramp-up of production capacities, including the required supply chain, will significantly influence whether the growth rate follows an S-curve or a linear pattern. A major precondition for expanding the required BEV infrastructure is supportive policy measures.

There is no clear preference in the literature for S-curve or linear growth patterns for technology transitions. Although historic literature favours the S-curve growth theory (Vernon 1966) [23], contemporary technology developments, such as wind and solar energy, have grown linearly or even exponentially. Therefore, three different growth scenarios have been calculated. The combination of S-curve and linear growth based on the unweighted average of the two is included. The sales figures for ICE cars can be derived according to the three different scenarios for the production of BEVs under the assumptions presented in Section 2. In addition to the annual sales figures, the cumulative sales that the manufacturers expect up to 2040 are also shown in the following graphs under the three grows scenarios (Figures 10–12).

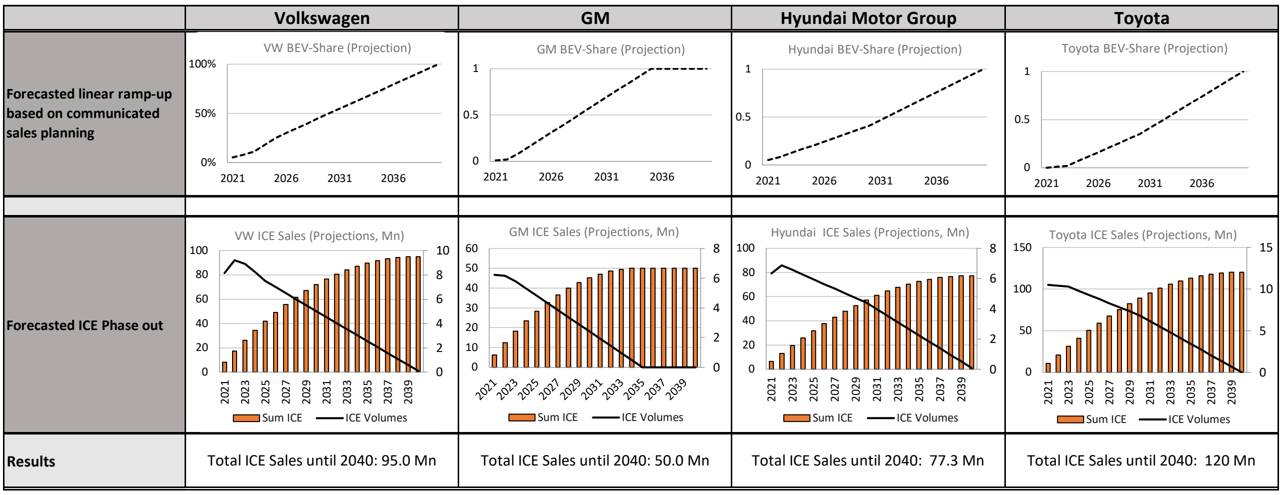


Figure 10. Linear BEV-transition scenario.

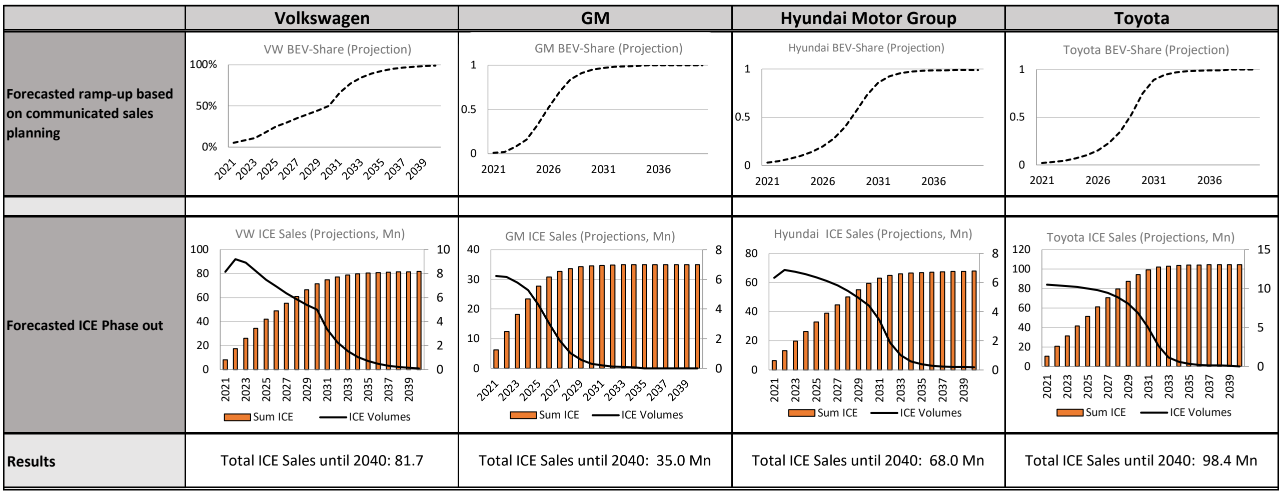


Figure 11. S-curve BEV transition scenario.

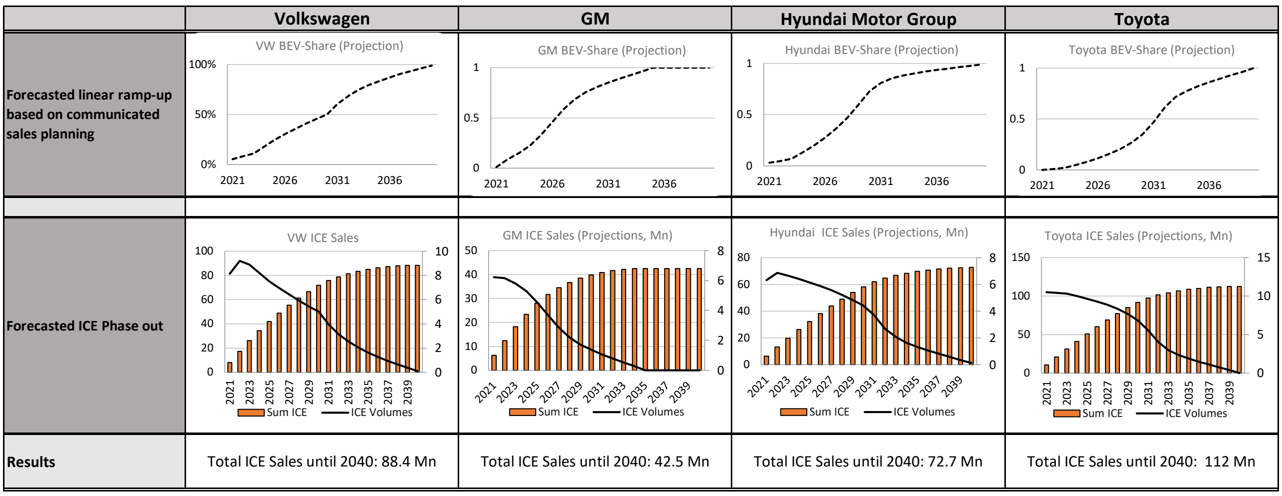


Figure 12. Combined BEV transition scenario.

The linear transition can be understood as a more pessimistic transition scenario or an upper boundary for the number of ICE vehicles produced. In contrast, the exponential S-curve ramp-up represents a more optimistic scenario for the growth of BEVs, with fewer ICEs entering the market over time. Whereas the S-curve pattern describes the upper end of the possible development of manufactured ICE vehicles and the linear pattern the lower end, the combination of both represents the median pattern of development, which is defined as the base case in this analysis. Based on the manufacturers' plans published up to May 2022, the following overall figures for the planned cumulative sale of ICE cars up to 2040 can be forecast.

The transition scenarios and the resulting cumulative sum of ICE sales by the four car manufacturers are the basis upon which global developments are determined. The manufacturers analysed cover 40% of the global market. As mass producers with broad portfolios of models (small cars, middle class, and premium), they cover all segments of the market and can be regarded as a representative sample of the global automotive market. Therefore, the different results for transition pathways at the company level are the foundations for the calculation of the global transition scenarios. These calculation are performed on the basis of weighted averages, and the weighting is based on the respective market share of each manufacturer in 2021.

Figure 13 shows the different transition scenarios of the car manufacturers and the resulting global transition. Toyota currently has the most-conservative plans in terms of the reduction of ICE vehicle manufacture, and its projected development is described as linear growth. In contrast, GM's plans are the most ambitious among the companies analysed, and are therefore calculated with assumed S-curve growth. The global transition scenario is slightly below the (unweighted) average of the four manufacturers in response to Toyota's weight as the largest manufacturer. This underlines how critical are the plans of the world's largest manufacturers, Toyota and Volkswagen, which have less-ambitious plans than GM (see Table 14). Based on these global scenarios for the transition towards BEVs, the expected global sales of ICE cars were estimated in the same way as those for the individual manufacturers, including the upper and lower boundaries and the base case.

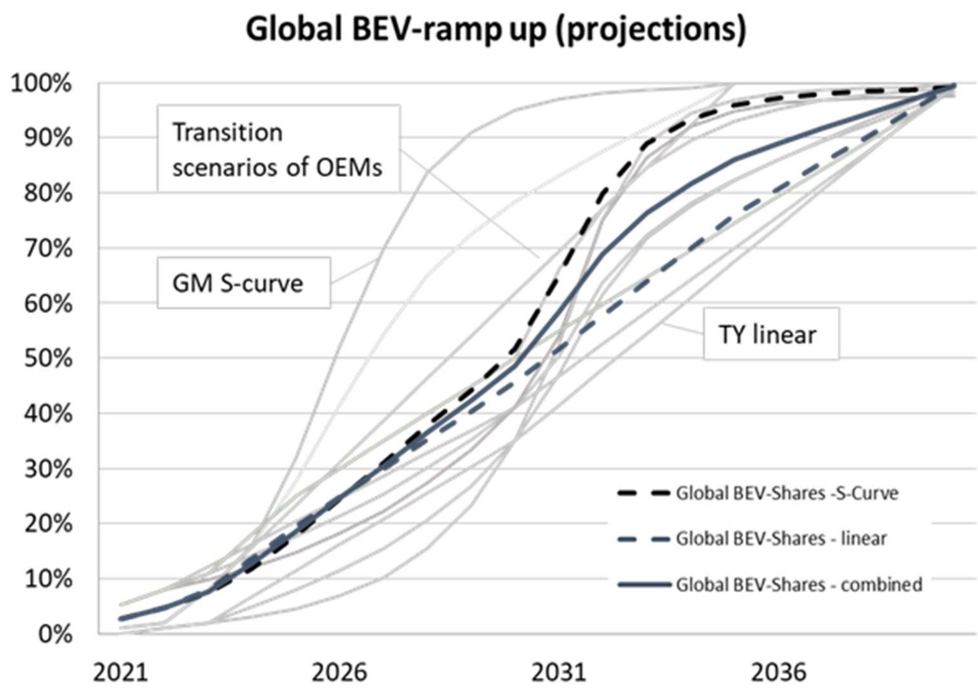


Figure 13. Global BEV ramp-up (projections).

Table 14. Forecast car manufacturer plans for total ICE car sales up to 2040 (in millions).

	VW Group	Toyota	Hyundai/Kia	GM
Upper boundary (linear)	95.0	120.1	77.3	50.0
Lower boundary (S-curve)	81.7	104.5	68.0	35.0
Base case (combined)	88.4	112.3	72.7	42.5

3.4. Results: Calculated Possible ICE Passenger Vehicle Sales Based on Published Manufacturers' Plans

Based on the published plans of the four main manufacture and the methodology described in Section 2, the cumulative amounts of ICE LDVs sold before they are phased out have been calculated, with a minimum of 723 million ICE LDVs and a maximum of 789 million (Figure 14).

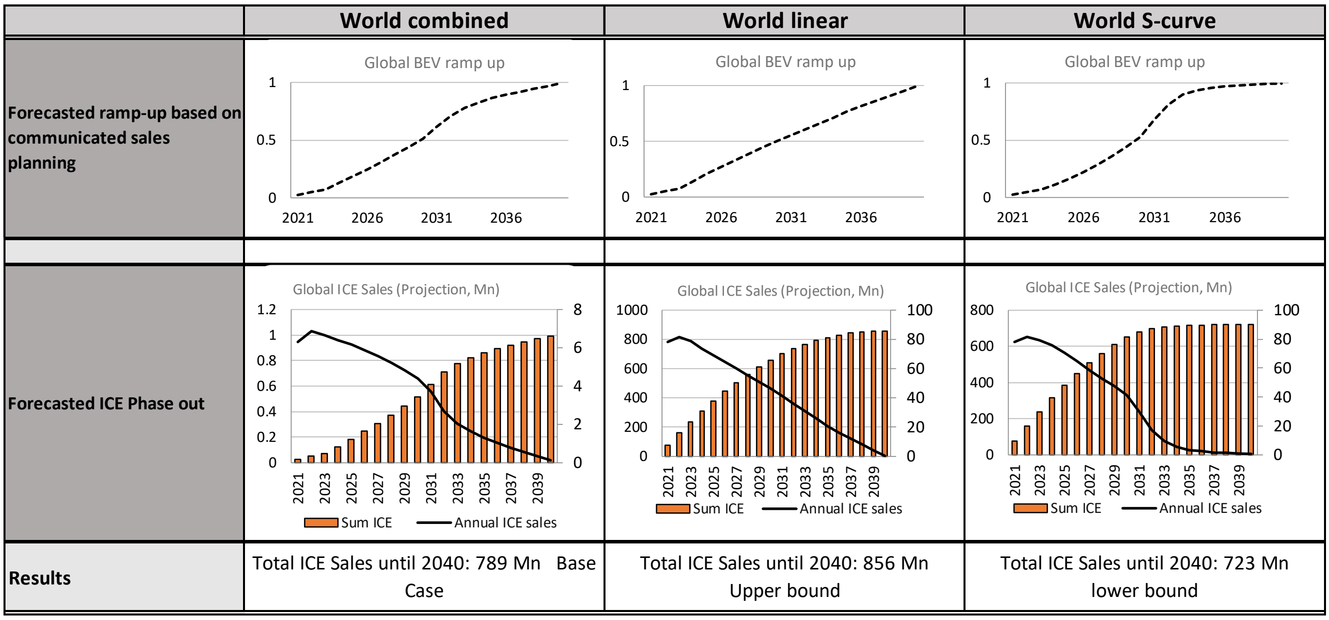


Figure 14. Projected total ICE LDV sales up to 2040.

4. Gap Analysis: 1.5 °C Pathway Versus Car Industry Plans

In Section 2 of this analysis, the permitted number of ICE car sales remaining globally under a 1.5 °C carbon budget (67% likelihood) was calculated to be a maximum of 388.6 million LDVs. It was assumed that the fleet structure in the four engine classes (see Table 10) will remain unchanged throughout the entire scenario period.

In Section 3, the uptake of BEVs and the possible reduction in ICE vehicles were assessed based on the published plans of the four major car manufacturers. Therefore, the scenario in Section 2 can be considered the 1.5 °C pathway and the scenario in Section 3 the 'current policy' scenario. In this section, we compare both scenarios and perform a gap analysis.

4.1. Comparison of Global Sales under Two Scenarios

Under the 'current policy' scenario, global ICE vehicle manufacture exceeds the number of sales consistent with the 1.5 °C carbon budget by a minimum of 334 million ICE cars and a maximum of 467 million. Table 15 compares the results for the 1.5 °C scenario with those of the 'current policy' scenario.

Table 15. Comparison of four global ICE vehicle sales scenarios.

		1.5 °C	Lower Boundary	Base Case	Upper Boundary
ICE vehicles (in millions)		388.6	723	789	856
Cumulative ICE sales—calculated overshoot	[million ICE]		334.4	400.4	467.4
Percentage overshoot	[%]		86%	103%	120%
Total cumulative CO_2 (2020–2050)	[million tCO_2]	52,902	98,426	107,411	116,532
Cumulative CO_2 emissions—calculated overshoot	[million tCO_2)	-	45,524	54,509	63,630
Calculated percentage overshoot	[%]	-	186%	203%	220%

The results clearly show that the plans of the main four global car manufacturers to phase-out ICE vehicles are inconsistent with a 1.5 °C pathway. Even when we consider that the estimates of the ICE vehicles produced based on published plans are relatively vague, the likelihood that, under current conditions, twice as many ICE vehicles will be sold as are permitted under the 1.5 °C carbon budget is almost 100%. Figures 15 and 16 compare the calculated sales of ICE LDVs and BEVs required under the 1.5 °C pathway. Under current plans, global car manufacturers will implement the transition far too slowly. Global car production must shift entirely to all-electric cars by 2030, whereas manufacturers project a share of only 52% at that time.

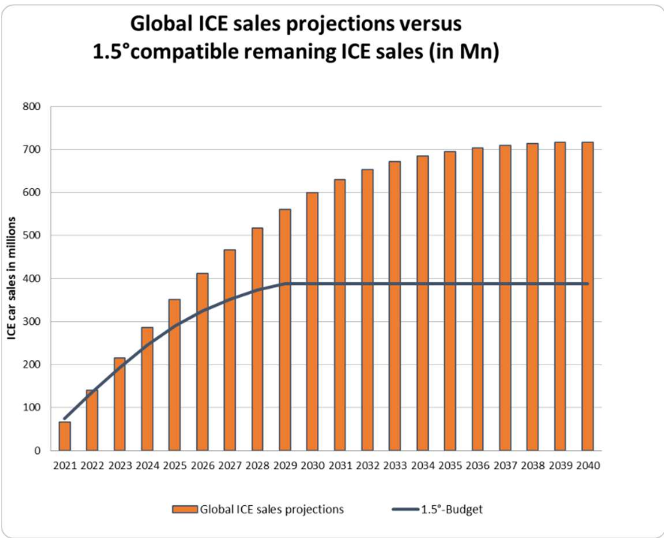


Figure 15. Global ICE LDV sales projections versus 1.5 °C-compatible remaining ICE LDV sales.

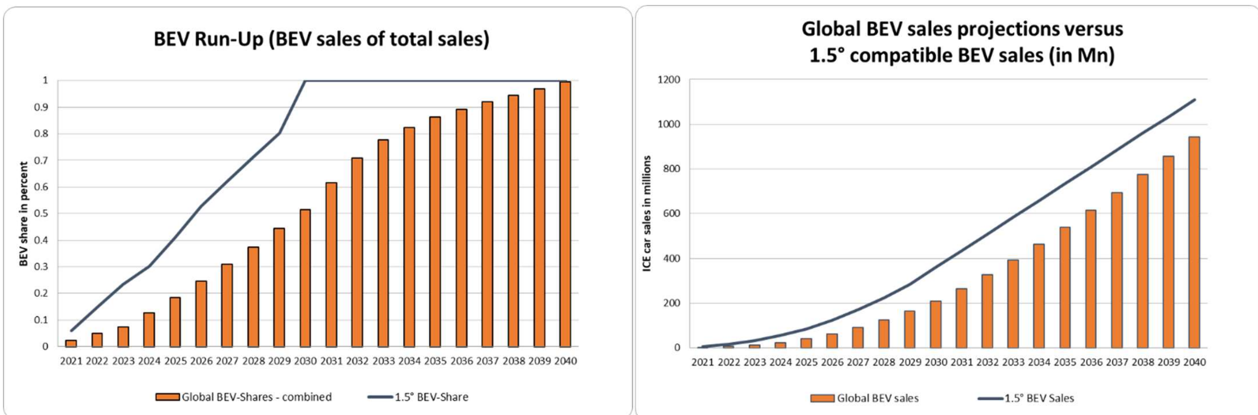


Figure 16. The BEV transition: necessary vs. projected BEV sales.

The cumulative remaining carbon budget for LDVs with ICEs under the 1.5 °C pathway is calculated to be 52 $GtCO_2$ (Teske et al., 2022 [3]). The calculated ICE phase-out trajectory under the 'current policy' scenario will lead to minimum cumulative carbon emissions (2020–2050) of 98 $GtCO_2$ and maximum of 116 $GtCO_2$. These overshoot emissions (46 $GtCO_2$) are in the order of the cumulative carbon budget of the global buildings sector (Chatterjee et al., 2022) [24] and are therefore very unlikely be compensated by other sectors.

4.2. Manufacturer-Specific Results

Table 16 shows the large spread of the four manufacturers' ambitions to organize the transition from ICEs to BEVs.

Table 16. Expected ICE sales overshoots of the key manufacturers relative to the 1.5 °C requirement.

	VW Group	Toyota	Hyundai/Kia	GM
Overshoot in % [upper boundary; lower boundary]	**95%** [109%; 80%]	**136%** [152%; 120%]	**114%** [128%; 101%]	**49%** [75%; 23%]
Overshoot in millions of ICE vehicles	**367.4** [425.1; 311.2]	**527.6** [590.8; 464.4]	**444.5** [479.9; 391.2]	**190.2** [292.3; 88]

4.2.1. General Motors

The projections for GM are the most ambitious, based on 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 analysed. GM has developed its own "Ultium" BEV architecture (MT 2022a) [25] and has invested in battery factories together with LG Chem. A wide range of BEV models has also been announced (MT 2022a) [26]. With its Chinese joint ventures, GM achieved notable EV shares in their sales in 2021. However, this was mainly due to the success of one model, the Hongguang Mini EV, which sold 420,000 units in China (Nikkei Asia 2022) [27]. Currently, GM offers its own four BEV models and sold around 25,000 BEVs in their US home market in 2021 (GM 2022) [28]. However, based on the projections above, GM will still exceed the 1.5 °C-compatible number of ICE car sales by 50%.

4.2.2. Volkswagen

The Volkswagen Group sold 452,900 BEVs in 2021. With a global market share of 10%, the Volkswagen Group was the third largest BEV manufacturer behind Tesla and SAIC (Inside EV 2022a) [29]. Volkswagen currently offers a total of 14 BEV models across all its brands (except Lamborghini and Bentley) based on its all-electric platforms. A follow-up "Scalable Systems Platform" is under development. Since June 2020, Volkswagen's factory in Zwickau (Germany) has switched to BEV-only production (VW 2022a) [30]. The company is in the process of transitioning additional factories to BEV production (VW 2022b) [31] and is investing in its own battery-cell production, with the first factories to start production in 2025 (Germany Federal Government 2022) [32].

Despite having a favourable starting position among the companies analysed, Volkswagen pursues a comparatively slow transition strategy, with—according to currently published BEV sales goals of the group—only linear growth until 2030 (see Table 16). Therefore, according to projections, Volkswagen is planning to sell nearly double the number of ICE cars that is compatible with a 1.5 °C scenario.

4.2.3. Hyundai/Kia

With 216,000 BEVs sold in 2021, Hyundai/Kia was the fifth largest BEV producer globally. In the USA, Hyundai/Kia had the second largest BEV sales after Tesla (InsideEV 2022b) [33]. Hyundai, Kia, and Genesis (Hyundai's luxury brand) are currently offering six BEV models and are planning to broaden their portfolio, adding up to 29 models before

2030 (InsideEV 2022c, [34] ElecTrek 2022 [35]). While placing more emphasis on BEVs, Hyundai/Kia are pursuing a two-pronged strategy, including fuel-cell electric vehicles (FCEV) in their transition away from ICEs. Hyundai is currently offering one FCEV model, the Hyundai Nexo, which has been in production since 2018. Because it is less efficient than BEVs, the fuel-cell technology in cars is controversial among analysts in terms of its competitiveness with BEVs (Forbes 2020) [36]. In the case of Hyundai/Kia's planned transition away from ICE cars, the calculated ICE sales will lead to 445 million vehicles, 114% more than is consistent with the 1.5 °C scenario.

4.2.4. Toyota

Toyota launched its first BEV model in April 2022, albeit with limited availability as production is only expected to pick up significantly by 2023 (Toyota 2022) [37]. Entering the market so late is a consequence of Toyota's strategy, which for a long time exclusively focused on full hybrids, plug-in hybrids, and FCEVs. A shift towards BEVs was announced in December of 2021 (TheDrive 2021) [38]. Toyota plans to sell only about 3.5 million zero-emission cars by 2030, which according to our analysis, will amount to about one third of its sales. Therefore, Toyota alone will sell 528 million ICE cars more than the calculated 388 million ICE vehicles permitted under the 1.5 °C benchmark.

5. Conclusions

The IPCC identified the global carbon budget required to achieve 1.5 °C warming (with 67% likelihood) as 400 $GtCO_2$ between 2020 and 2050 (IPCC AR6, 2021). Considering the use of fossil fuels in other sectors of the economy, the CO_2 budget for LDVs is around 52 $GtCO_2$. Based on current fuel efficiencies and car usage, just under 400 million cars with fossil-fuel-based ICEs can be manufactured and sold before their production must be phased-out. In comparison to global annual LDV sales, the automotive industry must completely cease production of ICE vehicles by 2030. The total decarbonization of the LDV sector will take an additional 20 years due to the technical lifetimes of ICE vehicles. The exact amount of remaining ICE vehicle sales will depend on their fuel efficiency, the annual kilometres driven, and the actual lifetime and/or usage of the cars themselves. Therefore, the projection is dependent upon these factors. However, even with significant improvements in fuel efficiencies, a phase-out of ICE cars is required to remain within the carbon budget and achieve zero CO_2 emission by 2050.

Finally, the early retirement of ICE vehicles between 2030 and 2050 would lead to a further reduction in CO_2. In this analysis, a vehicle's lifetime is assumed to be 15–20 years, leading to cumulative global CO_2 emissions between 2031 and 2050 of 17.8 $GtCO_2$—about 34% of the total carbon budget for LDVs.

The market reduction across all ICE vehicle types required to achieve a complete ICE phase-out by 2030 is 3–4% per year, on average, in this analysis. A 5-year delay in the ICE phase-out will result in an additional 10–15 $GtCO_2$ of CO_2 and—when combined with energy-related CO_2 emissions from other parts of the economy—is inconsistent with the 400 $GtCO_2$ carbon budget required to reach 1.5 °C warming (with 67% likelihood). More detailed quantification of the effects of such a delay on global carbon emissions and the mean global temperature rise requires more research and is beyond the scope of this analysis.

This analysis of expected global sales of ICE cars, projected on the basis of the plans of the four largest car manufacturers (Toyota, VW, Hyundai and GM), shows that the business plans of established car companies aim to produce significantly more ICE vehicles than is permitted under a 1.5 °C-compliant trajectory. The calculated amount of ICE vehicles that will be manufactured under the current plans of the four main car manufacturers will be twice as high as the amount permitted to remain within 1.5 °C of global warming and is therefore incompatible with the Paris Climate Agreement.

While this analysis focusses on energy related carbon emissions from LDVs, the authors would like to highlight that a shift from individual transport systems, such as LDVs, to public transport and to non-energy transport systems, such as cycling and walking, is also essential and will reduce the numbers of new BEVs required. Furthermore, the chosen materials for LDV manufacturing impact carbon budgets as well (Spreafico 2021) [39].

Limitations

The analysis is based on the latest available statistic and automotive industry data. However, specific market shares by vehicle class for 2020 and 2021 are estimated as statistical data was not available at the time of writing.

The assumed ICE LDV retirement rates and vehicle lifetimes are subject to high uncertainties. Export rates of used cars from industrialized countries to developing countries were not considered in this analysis and may prolong the estimated lifetime for ICE LDVs significantly. A longer usage of ICE LDV would reduce the ICE LDV production limit under a 400 $GtCO_2$ carbon budget further.

The gap-analysis '1.5 °C Pathway Versus Car Industry Plans' is based on publicly available information, any changes regarding the LDV manufacturing plans by the four major manufacturers since May 2022 are not considered.

Finally, the required electricity to supply electric vehicles must come from carbon-free electricity to remain within the calculated carbon budget. A slower decarbonization rate of the electricity sector will increase the carbon emissions of battery-electric vehicles accordingly.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Role of Decarbonization of the Electricity Sector

The advantage of battery electric vehicles (BEVs) in terms of their CO_2 emissions assumes that the electricity consumed is generated with decreasing specific CO_2 emissions 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. 2022) [8]. In the OECM, fossil-fuel-based electricity generation will be phased out globally by 2050 and replaced entirely by renewable power plants. Table 14 shows the electricity generation shares by technology between 2020 and 2050.

Furthermore, the global electricity demand will increase, due to the electrification of the transport sector, from around 400 TWh per year in 2020 to around 5000 TWh by 2040 and will remain at that level thereafter. To decarbonize the road transport sector, it is vital to decarbonize the electricity sector in parallel, and to generate the additional electricity demand entirely with renewable power plants.

Table A1. 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/kW]	509	290	136	53	24	0

(*) Hydrogen produced with 100% renewable electricity.

References

1. EU. European Council, Press Release 29 June 2022. Fit for 55 Package: Council Reaches General Approaches Relating to Emissions Reductions and Their Social Impacts. 2022. Available online: https://www.consilium.europa.eu/en/press/press-releases/2022/06/29/fit-for-55-council-reaches-general-approaches-relating-to-emissions-reductions-and-removals-and-their-social-impacts/ (accessed on 20 October 2022).
2. IEA. Definition of Light-Duty Vehicles (LDV) Is According to the International Energy Agency (IEA). Available online: https://www.iea.org/data-and-statistics/charts/total-light-duty-vehicle-sales-2010-2019 (accessed on 20 October 2022).
3. Teske, S.; Niklas, S. Decarbonisation Pathways for Transport. In *Achieving the Paris Climate Agreement Goals*; Teske, S., Ed.; Springer: Cham, Switzerland, 2022. [CrossRef]
4. OICA. International Organization of Motor Vehicles Manufacturers Website. 2021. Available online: https://www.oica.net/category/production-statistics/2021-statistics/ (accessed on 28 October 2021).
5. Bratzel, S. Center of Automotive Management. E-Mobility: Market Trends in the Core Regions of Europe and China in Q1 2021. 2021. Available online: https://auto-institut.de/en/automotiveinnovations/emobility/e-mobilitaet-marktrends-in-den-kernregionen-europa-und-china-im-1-quartal-2021/ (accessed on 28 September 2021).
6. Masson-Delmotte, V.; Zhai, P.; Pirani, A.; Connors, S.L.; Péan, C.; Berger, S.; Caud, N.; Chen, Y.; Goldfarb, L.; Gomis, M.I.; et al. (Eds.) *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to The Sixth Assessment Report of the Intergovernmental Panel on Climate Change*; Cambridge University Press: Cambridge, UK, 2021.
7. Teske, S.; Niklas, S.; Atherton, A.; Kelly, S.; Herring, J. *Sectoral Pathways to Net Zero Emissions*; University of Technology Sydney: Sydney, Australia, 2020.
8. Teske, S.; Niklas, S.; Talwar, S. Decarbonisation pathways for industries. In *Achieving the Paris Climate Agreement Goals*; Teske, S., Ed.; Springer: Cham, Switzerland, 2022. [CrossRef]
9. IEA. *Net-Zero by 2050—A Roadmap for the Global Energy Sector*; IEA: Paris, France, 2021.
10. Teske, S.; Pregger, T. OECM 1.5 °C Pathway for the Global Energy Supply. In *Achieving the Paris Climate Agreement Goals*; Teske, S., Ed.; Springer: Cham, Switzerland, 2022. [CrossRef]
11. Teske, S.; Niklas, S.; Langdon, R. TUMI Transport Outlook 1.5 °C—A Global Scenario to Decarbonise Transport. Report Prepared by the University of Technology Sydney for the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ) GmbH. 2021. Available online: https://www.transformative-mobility.org/assets/publications/TUMI-Transport-Outlook.pdf (accessed on 28 September 2021).
12. ACEA. Interactive Map–CO2 Emissions from New Passenger Cars in the EU, by Country. 2020. Available online: https://www.acea.auto/figure/interactive-map-co2-emissions-from-new-passenger-cars-in-the-eu-by-country/ (accessed on 18 October 2021).
13. Held, M.; Rosat, N.; Georges, G.; Pengg, H.; Boulouchos, K. Lifespans of passenger cars in Europe: Empirical modelling of fleet turnover dynamics. *Eur. Transp. Res. Rev.* **2020**, *13*, 9. [CrossRef]
14. Marrero, G.; López, J.; González, R.M. Car usage, CO_2 emissions and fuel taxes in Europe. *J. Span. Econ. Assoc.* **2019**, *11*, 203–241. [CrossRef]
15. Statista. Average Annual Number of Kilometers Driven by Circulating Vehicles in the United States from 2013 to 2020. 2021. Available online: https://www.statista.com/statistics/1266927/us-average-annual-mileage-of-vehicles-in-use/ (accessed on 28 September 2021).

16. ABS. Australian Bureau of Statistic, Survey of Motor Vehicle Use, Australia. 21 December 2020. Available online: https://www.abs.gov.au/statistics/industry/tourism-and-transport/survey-motor-vehicle-use-australia/latest-release (accessed on 28 September 2021).
17. IEA. Global Car Sales by Key Markets, 2005–2020. International Energy Agency. Online Database. 2020. Available online: https://www.iea.org/data-and-statistics/charts/global-car-sales-by-key-markets-2005-2020 (accessed on 17 March 2020).
18. OICA. International Organization of Motor Vehicles Manufacturers, Website. Online Database. 2021. Available online: https://www.oica.net/category/sales-statistics/ (accessed on 28 September 2021).
19. UBA. Umweltbundesamt Climate Change, 28/2022, CO2-Emissionsfaktoren für fossile Brennstoffe Aktualisierung 2022. 2022. Available online: https://www.umweltbundesamt.de/publikationen/co2-emissionsfaktoren-fuer-fossile-brennstoffe-0 (accessed on 28 September 2021).
20. BNEF. Bloomberg New Energy Finance, Vehicle Outlook. 2022. Available online: https://about.bnef.com/electric-vehicle-outlook/ (accessed on 25 September 2022).
21. Menzel, S.; Hubrik, F.; Handelblatt. Handelsblatt Autogipfel, Volkswagen Kündigt das Ende des Verbrennungsmotors an. 4 December 2018. Available online: https://www.handelsblatt.com/unternehmen/industrie/auto-von-morgen/handelsblatt-autogipfel-volkswagen-kuendigt-das-ende-des-verbrennungsmotors-an/23715746.html (accessed on 20 October 2022).
22. NBER. Macrohistoric Database, St. Louis Fed. Accessed via Macrobond. Available online: https://fred.stlouisfed.org/release?rid=257 (accessed on 28 September 2022).
23. Vernon, R. International investment and international trade in the product cycle. *Q. J. Econ.* **1966**, *80*, 190–207. [CrossRef]
24. Chatterjee, S.; Kiss, B.; Ürge-Vorsatz, D.; Teske, S. Decarbonization pathways for buildings. In *Achieving the Paris Climate Agreement Goals*; Teske, S., Ed.; Springer: Cham, Switzerland, 2022. [CrossRef]
25. Motortrend. GM's Ultium Electric Car Platform Technology: Everything You Need to Know. Online Magazine. March 2022. Available online: https://www.motortrend.com/news/gm-ultium-platform-technology-explained/ (accessed on 28 September 2022).
26. Motortrend. Keeping Up with GM EV News Is Like Drinking from a Firehose. Online Magazine. February 2022. Available online: https://www.motortrend.com/news/general-motors-2021-earnings-ev-product-news/ (accessed on 28 September 2022).
27. Nikkei Asia. GM Looks to Catch Tesla in China with New Low-Cost EV. Online Magazine. April 2022. Available online: https://asia.nikkei.com/Business/Automobiles/GM-looks-to-catch-Tesla-in-China-with-new-low-cost-EV (accessed on 28 September 2022).
28. GM. U.S. GM Sales Down 43 Percent to 440,745 Units in Fourth Quarter 2021. GM Authority. Online Magazine. March 2022. Available online: https://gmauthority.com/blog/2022/01/gm-sales-figures-numbers-results-united-states-q4-2021/ (accessed on 28 September 2022).
29. InsideEV. World's Top 5 EV Automotive Groups Ranked by Sales: 2021. Inside EV. Online Magazine. February 2022. Available online: https://insideevs.com/news/564800/world-top-oem-sales-2021/ (accessed on 28 September 2022).
30. VW. VW Company Website. 2022. Available online: https://www.volkswagen-sachsen.de/de/unternehmen/pressemitteilungen/pm_transformation-schreitet-voran.html (accessed on 28 September 2022).
31. VW. VW Company Website. 2022. Available online: 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 (accessed on 28 September 2022).
32. German Federal Government. Transformation to a Climate-Neutral Industry. Official Website of the German Federal Government. 2022. Available online: https://www.bundesregierung.de/breg-en/news/battery-cell-plant-vw-salzgitter-2060434 (accessed on 28 September 2022).
33. InsideEV. US: Hyundai Motor Group "Breaks from BEV Pack" in Q1 2022. Online Magazine. March 2022. Available online: https://insideevs.com/news/586090/us-electric-car-sales-hyundai-2022q1/ (accessed on 28 September 2022).
34. InsideEV. Hyundai Announces Accelerated Electrification Strategy. Online Magazine. March 2022. Available online: https://insideevs.com/news/571125/hyundai-accelerated-electrification-strategy/ (accessed on 28 September 2022).
35. ElecTrek. 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. Available online: 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/ (accessed on 28 September 2022).
36. Forbes. Why Hydrogen Will Never Be the Future of Electric Cars. Online Magazine. July 2020. Available online: https://www.forbes.com/sites/jamesmorris/2020/07/04/why-hydrogen-will-never-be-the-future-of-electric-cars/ (accessed on 28 September 2022).
37. Toyota. Toyota Newsroom, Company Website. 2022. Available online: https://pressroom.toyota.com/the-future-is-now-toyota-launches-all-new-bz4x-suv-battery-electric-vehicle/ (accessed on 28 September 2022).
38. TheDrive. Toyota Has a New EV Strategy. Here's Where We Think It's Headed. Online Magazine. December 2021. Available online: https://www.thedrive.com/tech/43978/toyota-has-a-new-ev-strategy-heres-where-we-think-its-headed (accessed on 28 September 2022).
39. Spreafico, C. Can modified components make cars greener? A life cycle assessment. *J. Clean. Prod.* **2021**, *307*, 127190. Available online: https://www.sciencedirect.com/science/article/pii/S0959652621014098 (accessed on 28 September 2022). [CrossRef]