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PATHWAYS TO DECARBONIZATION: THE EUROPEAN PASSENGER CAR MARKET IN THE YEARS 2021–2035

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EXECUTIVE SUMMARY

The European Green Deal, the climate and green growth strategy of the European Union (EU), sets the objective of achieving net-zero greenhouse gas (GHG) emissions by 2050. As part of the roadmap to achieve its climate-neutrality goal, the European Commission will come forward with a proposal for revised carbon dioxide (CO_2) targets for new passenger cars and vans by the middle of 2021. The targets currently in place require a 15% reduction in type-approval CO_2 emissions for new passenger cars by 2025, relative to 2021, and a 37.5% reduction by 2030. With these current requirements, the envisioned economy-wide GHG reduction target of at least 55% by 2030 compared to 1990 is projected to be missed, as is the EU Green Deal target for transport of -90% GHG emissions by 2050 compared to 1990 (Buysse et al., 2021). These economy-wide and transport targets therefore require revising and strengthening EU sectoral policies and regulations across the board. This paper explores how the passenger car CO_2 standards specifically could be strengthened cost-effectively.

The scenarios investigated in this paper assess the CO_2 reduction potential and associated estimated costs for various policy pathways:

» In the **Adopted Policies** scenario, manufacturers comply with the currently established targets of **-15% by 2025** and **-37.5% by 2030** but make no efforts to exceed the necessary levels of CO_2 reduction, such as through increased electric vehicle deployment. The remaining potential of internal combustion engine (ICE) vehicles is untouched, and electric vehicle market shares stagnate from 2030 onwards.

» The **Lower Ambition** scenario assumes that current targets are strengthened to **-20% by 2025** and **-50% by 2030**, plus the introduction of a -70% target for 2035. It thereby ensures that manufacturers tap some of the remaining ICE potential (reducing CO_2 by about 1% annually) and further increase the market share of electric vehicles, so that battery electric vehicles (BEVs) account for about half of new car sales by 2035.

» In the **Moderate Ambition** scenario, the CO_2 targets are increased to **-30% by 2025**, **-70% by 2030**, and -100% by 2035. To comply, vehicle manufacturers must exploit most of the remaining potential of ICEs at a rate of about 4% CO_2 reduction annually in the Worldwide Harmonized Light Vehicle Test Procedure (WLTP) between 2021 and 2025, which includes a reduction in vehicle mass and transitioning to mild hybrid vehicles. In addition, plug-in hybrid electric vehicles (PHEVs) are phased out and replaced by more cost-efficient BEVs faster than in the Lower Ambition scenario. BEVs reach a market penetration of about 50% by 2030 and 100% by 2035.

» In the **Higher Ambition** scenario, full CO_2 reduction (**-100%**) in WLTP of the new car fleet is achieved **by 2030** due to a rapid transition towards battery electric vehicles (BEVs) with remaining ICE potential fully exploited in the transition years.

For all scenarios, direct manufacturing costs increase compared to the 2021 baseline, from about €400 in the Adopted Policies scenario in 2025 to about €1,700 in the Higher Ambition scenario in 2030 (Table ES1). In 2035, incremental manufacturing costs decline compared to 2030, mainly due to improved learning for electric vehicle technologies. Fuel cost savings throughout the lifetime of the vehicle make up for these initial investments in improved vehicle technologies. From a consumer perspective, for 2025, the Moderate Ambition and Higher Ambition scenarios provide the most favorable cost-benefit: Initial technology investments are fully paid for within four to six years of ownership, due to lower fuel cost. For 2030, the Higher Ambition scenario ensure the quickest payback period (two years) and highest savings. For 2035, technology investments pay back within one to two years for all scenarios except the Adopted Policies scenario, and savings are highest for the Moderate and Higher Ambition scenarios. In addition to fuel cost savings, calculations from a societal perspective also include the avoided external cost of CO_2. For society, in all years, those scenarios with the highest CO_2 reduction are also the scenarios that provide the greatest savings—in other words, the higher CO_2 savings, the higher the benefits for society.

Table ES1. Summary of cost-benefit calculations for all main scenarios from a manufacturer, consumer, and societal perspective, compared to a 2021 baseline.

Scenario	Average new car CO_2 level	Additional manufacturing costs	Consumer payback period	Net consumer savings years 0-8	Societal savings vehicle lifetime
2025					
Adopted Policies	-15%	382 €	>8	-83 €	-995 €
Lower Ambition	-20%	671 €	>8	-229 €	-17 €
Moderate Ambition	-30%	804 €	4	600 €	580 €
Higher Ambition	-40%	1,199 €	6	420 €	987 €
2030					
Adopted Policies	-37.5%	938 €	6	331 €	139 €
Lower Ambition	-50%	1,223 €	4	913 €	1,752 €
Moderate Ambition	-70%	1,380 €	3	1,889 €	3,422 €
Higher Ambition	-100%	1,703 €	2	3,107 €	5,660 €
2035					
Adopted Policies	-37.5%	695 €	3	778 €	416 €
Lower Ambition	-70%	930 €	1	2,457 €	3,977 €
Moderate Ambition	-100%	1,079 €	1	4,250 €	6,856 €
Higher Ambition	-100%	1,079 €	1	4,250 €	6,856 €

Two sensitivity scenarios illustrate the potential role of synthetic fuels (eFuel) and fuel cell vehicles (FCVs) in achieving emission reductions. The Moderate Ambition (PHEV & eFuel) scenario assumes manufacturers meet the Moderate Ambition CO_2 targets by relying heavily on PHEVs and eFuel instead of BEVs. As a result, direct manufacturing costs increase by more than 60% by 2030 and are more than double those of the Moderate Ambition scenario by 2035 (Table ES2). Savings for consumers and society are lost, turning instead into high costs without an opportunity to pay back technology and fuel investments within the typical holding period or lifetime of a vehicle. The Moderate Ambition (Fuel Cell) scenario assumes that from 2030 onwards, FCVs will be deployed, reaching a market share of 40% by 2035. Manufacturing costs are estimated to increase only slightly compared to the Moderate Ambition scenario. Consumer savings are lower, although payback is still reached within the second year of ownership. From a societal perspective, savings are about 25% lower than in the main scenario.

Table ES2. Summary of cost-benefit calculations for the Moderate Ambition policy scenarios from a manufacturer, consumer, and societal perspective, compared to a 2021 baseline.

Scenario	Average new car CO_2 level	Additional manufacturing costs	Consumer payback period	Net consumer savings years 0-8	Societal savings vehicle lifetime
2030					
Moderate Ambition	-70%	1,380 €	3	1,889 €	3,422 €
MA (PHEV & eFuel)	-70%	2,163 €	>8	-364 €	1,142 €
MA (Fuel Cell)	*identical to Moderate Ambition main scenario*				
2035					
Moderate Ambition	-100%	1,079 €	1	4,250 €	6,856 €
MA (PHEV & eFuel)	-90%	2,663 €	>8	-1,079 €	-1,073 €
MA (Fuel Cell)	-100%	1,452 €	2	2,560 €	5,170 €

The following conclusions can be drawn from the analysis:

» To meet its agreed climate protection targets, the EU needs to revise its sector-specific CO_2 reduction targets, including those for passenger cars. The Lower Ambition scenario would bring CO_2 levels closer to the EU's targets, resulting in cumulative real-world CO_2 savings of 2,040 metric tons (Mt) between 2021 and 2050, but would still miss full decarbonization by 2050. The **Moderate Ambition scenario** (-2,970 Mt CO_2) **and especially the Higher Ambition scenario** (-3,520 Mt CO_2) **would be more favorable from a climate protection perspective** (Buysse et al., 2021).

» All scenarios require larger investments in advanced vehicle technologies, with the highest incremental technology costs reached in model year 2030. Taking into account fuel and CO_2 emission savings, the Moderate and Higher Ambition scenarios provide the most favorable consumer payback period (two to three years) and societal lifetime savings (about €3,400 to €6,100) in 2030. For 2035, all three advanced scenarios offer a favorable cost-benefit ratio both from a consumer and society perspective, with the Higher Ambition scenario providing the highest savings for society. For 2025, the Moderate Ambition scenario offers the lowest consumer payback period (four years), combined with a reasonable outlook from a society perspective. **In summary, the Higher Ambition scenario provides the highest benefits throughout the years 2025–2035.**

» **Relying on PHEVs in combination with eFuel has very limited CO_2 reduction potential and extraordinarily high cost.** The 2035 CO_2 reduction target of the Moderate Ambition scenario is missed. Introducing any crediting mechanism for eFuel into the new vehicle CO_2 regulation might also be unduly extended to similar credits for biofuels, with much lower cost but significantly worse environmental and climate impacts than eFuel from renewable sources.

» FCVs may provide a viable option for the passenger car segment, at least for 2030 and beyond. However, even optimistically assuming a high share of renewable hydrogen and following optimistic cost estimates from the hydrogen industry, the resulting **cost-benefit calculations for FCVs offer about 25% fewer societal benefits than a stronger uptake of BEVs provides.** Vehicle manufacturers may therefore be unwilling to develop an FCV production and distribution chain parallel to that of BEVs.

» **If manufacturers strive toward exploiting the benefits of the current credits for zero- and low-emission vehicles (ZLEVs)** (i.e., a 5% relaxation of their respective fleet targets), **this will neglect most of the available remaining technology potential of ICEs and/or fewer electric vehicles.** In order to tap all available potential, the 2025 and 2030 fleet targets would therefore need to be strengthened, and/or the ZLEV adjustment factors would need to be reduced.

- Despite the relatively short lead-time, **it is important to consider strengthening not only the 2030 fleet target but also the 2025 target, and to consider implementing annual targets in place of step-wise goals.** Reducing more CO_2 early increases cumulative savings for consumers and society and climate efficacy. Early CO_2 reductions also ensure a smoother technology uptake in anticipation of necessary CO_2 reductions towards 2030 and 2035.
- Any crediting scheme that awards credits in excess of reductions achieved reduces the effectiveness of the new vehicle CO_2 regulation. To avoid this effect, **credits for ZLEVs and eco-innovations should be set as low as appropriate and/or be phased out as early as possible. Enforcement of real-world emission reductions must improve** to ensure that any CO_2 reduction under the official test procedure is also reflected to the same extent under average real-world driving conditions. For example, PHEVs' current gap between type-approval and real-world performance discourages a transition toward more effective vehicle variants that show a higher electric range than is the case today. For the years 2030 and beyond, it is also important to **take into account differences in vehicle energy efficiency** for differentiating between electric vehicles.
- **A stronger reduction of new passenger car CO_2 emission levels is not a question of technology availability and cost.** All technologies considered for the analysis are in principle already available today. The cost-benefit calculations from both a consumer and society angle favor the main scenarios, especially for the years 2030 and afterward. Instead, whether the technology market shares that the scenarios assume will enter into effect depends on stringent regulatory targets, production capacities, re-charging and fueling infrastructure availability, and other external factors.

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ABBREVIATIONS

BEV	Battery electric vehicle
FCV	Fuel cell vehicle
HEV	Hybrid electric vehicle
ICE	Internal combustion engine
MHEV	Mild hybrid electric vehicle
NEDC	New European Driving Cycle
OMEGA	Optimization Model for reducing emissions of Greenhouse Gases from Automobiles
p.a.	Per annum
PHEV	Plug-in hybrid electric vehicle
WLTP	Worldwide Harmonized Light Vehicle Test Procedure
ZLEV	Zero- and low-emission vehicle

INTRODUCTION

In September 2020, the European Commission proposed raising the ambition of Europe's 2030 greenhouse gas (GHG) emissions reduction goal from at least 40% to at least 55%, compared to 1990 levels, with the intent of placing the EU on a credible pathway to meet its climate-neutrality goal. The proposal would anchor this increased target in the yet-to-be-passed European Climate Law. With this initiative, endorsed by the European Council and currently pending agreement with the European Parliament, the Commission would deliver on the roadmap set out in the European Green Deal—the long-term climate action plan adopted at the end of 2019 with the objective of achieving net-zero GHG emissions by 2050 in the European Union (EU).

The proposed revision of the 2030 target builds on an extensive Impact Assessment, which included economy-wide analyses of the expected GHG emissions reductions from the EU's adopted policies and of policy options available for stepping up the interim target ambition most cost-effectively. It concluded that, without substantial changes to the current policy framework that result in additional emissions reductions by 2030, the EU would only cut its 2050 GHG emissions by 60% below the 1990 baseline. The Commission thus committed to proposing, by June 2021, the necessary legislative actions to reach climate neutrality by mid-century.

The post-2020 legislation on tailpipe CO_2 emission standards for new light-duty vehicles is among the regulations that the EU will revise by mid-2021. The EU is expected to amend the heavy-duty CO_2 standards in 2022. The EU's new climate action initiatives prioritize cutting GHG emissions from transportation, as the sector accounts for a significant and growing share of the EU's total GHG emissions (around 21% in 2018) (European Commission, 2020a). Road transportation is by far the largest contributor to the sector's emissions (about 71% in 2018), with passenger cars constituting the largest source of road transportation emissions. However, road transportation is also the subsector with the highest emissions abatement potential (European Economic Area [EEA], 2020). Standards that regulate CO_2 emissions are generally regarded as the main policy instrument to capitalize on this potential.

With this paper, we seek to inform the upcoming review of the light-duty vehicle CO_2 regulation and the discussion of the level of CO_2 stringency that passenger cars can meet by 2030 and 2035 by identifying the most cost-effective CO_2 emission reduction strategies. We present vehicle technology cost curves for the European passenger car fleet in the 2021–2035 time frame, comprised of an analysis of vehicle technology packages that could be deployed to comply with future regulations up to 2035; the technology packages' estimated type-approval CO_2 reduction potential; and projected costs compared to a 2018 baseline. The study closely examines four emission reduction pathways, which differ in electric vehicle penetration and internal combustion engine (ICE) efficiency improvements attained in a given year. One scenario follows currently adopted CO_2 emission standards, while the other three scenarios include increasingly stronger targets. Two additional sensitivity scenarios investigate the effects of fuel cell vehicle (FCV) uptake and a potential crediting system for synthetic fuels, respectively.

DEFINITIONS AND DATA SOURCES

The scope of this paper covers new passenger cars offered in EEA, which includes member states of the EU, plus Iceland, Liechtenstein, and Norway, between the years 2021 and 2035. Passenger cars account for about 90% of the European light-duty vehicle market (Díaz et al., 2020). Light-commercial vehicles, which account for the remaining 10% of the market, are outside the scope of this paper. About one quarter of the passenger cars sold in Europe belong to the lower medium segment, also called the C segment (Díaz et al., 2020). If accounting for cross-over vehicles based on C-segment cars, nearly 50% of passenger cars in Europe fall under the definition of a lower medium segment vehicle. All emission and cost estimates in this paper are tailored to a VW Golf, which is the most popular lower medium segment vehicle model and the top-selling vehicle model overall, accounting for 3% of all new passenger car sales in Europe in 2019 (Díaz et al., 2020). As previous work has shown, estimates for the C segment serve as an accurate proxy for the emission and cost estimates for the average European new car fleet overall (Meszler et al., 2016).

Our analysis focuses on carbon dioxide (CO_2) emissions. We assume that vehicles comply with all current and future air pollutant emission regulations. Where required, we add the cost of extra exhaust emission treatment technology to ensure future regulatory compliance. We express all emissions figures in CO_2 as determined by the official test procedure of the EU, the Worldwide Harmonized Light Vehicle Test Procedure (WLTP). Actual tailpipe emissions of driving in real-world conditions are beyond the scope of this study, except for the cost-benefit calculations from a consumer and society perspective that complement the vehicle technology phase-in scenarios presented later in this paper.[1] Furthermore, the regulation, and hence this analysis, does not cover non-CO_2 GHG emissions or upstream GHG emitted during the production of, fuel, electricity, or the vehicle.

The year 2018 serves as the baseline for the analysis, so we calibrate the starting point of all estimates to the market situation at that time: 94% conventional ICE vehicles, 4% mild and full hybrid vehicles, 1% plug-in hybrid electric vehicles (PHEVs), and 1% battery electric vehicles (BEVs) (Díaz et al., 2020). The New European Driving Cycle (NEDC) set the fleet-average new car CO_2 level in 2018 at 120 grams per kilometer (g/km), converted to a level of 145 g/km in WLTP, using an average 1.21 conversion factor (Dornoff et al., 2020). Similarly, we estimate technology costs as direct manufacturing costs for the respective year expressed in Euros (€) for the year 2018. In comparison to direct manufacturing cost, retail costs also include indirect costs, such as research and development and warranty costs, but exclude any sales taxes.

Data on the CO_2 reduction potential and cost of various technologies, based on simulation modeling and bottom-up cost estimation work performed for the ICCT by the engineering services provider FEV, serve as an underlying basis for this analysis (Meszler et al., 2016). For improvements in road load (i.e., vehicle mass, aerodynamics, rolling resistance) and ICE vehicle technologies, including mild and full hybrid vehicles, we update this data using figures obtained from the automotive engineering services provider AVL (2020). We use the United States Environmental Protection Agency (EPA) Optimization Model for Reducing Emissions of Greenhouse Gases from Automobiles (OMEGA) to estimate the effects of learning on costs (U.S.

1 For conventional combustion engine vehicles, CO_2 emissions in real-world usage are found to be about 14% higher than the WLTP values indicate (Dornoff et al., 2020). The real-world energy consumption of electric and fuel cell vehicles is estimated to exceed WLTP values by a similar proportion (Allgemeiner Deutscher Automobil-Club, n.d.). In contrast, Plötz et al. (2020) found the average CO_2 emission level in real-world usage for PHEVs' to be two to four times higher than WLTP values indicated.

Environmental Protection Agency, 2016).[2] Also, we derive from OMEGA the cost estimates for complying with a future Euro 7 air pollutant emission standard, which for gasoline vehicles is assumed to be similar to the U.S. Tier 3 emission standard. The primary meta-source for cost data on electric vehicles is an ICCT study on electric vehicle costs in the United States (Lutsey & Nicholas, 2019), which we adapt to the European context and extend to 2035. In addition, we incorporate AVL data for fuel cell vehicle technology. For synthetic fuels, we calculated the decarbonization potential at a given cost subsidy level following the approach of an earlier ICCT study (Searle & Christensen, 2018).

2 Explicit OMEGA learning runs through 2030; data for 2031–2035 was developed by regressing the earlier data. For powertrain, extrapolated factors range from 0.6%–0.7% cost reduction p.a.; for road load, 0.4%–0.5% p.a.; for hybrids, 0.6%–0.9% p.a.

TECHNOLOGIES

Manufacturers can make use of an array of vehicle technologies to reduce the CO_2 level of their fleet. In the following section, we briefly describe the assumed effect of these technologies on WLTP CO_2 emissions and direct manufacturing costs.

INTERNAL COMBUSTION ENGINE (ICE) VEHICLES

In an earlier study, based on comprehensive vehicle simulations, it was estimated that for a **gasoline vehicle** of the C segment, CO_2 emissions in NEDC could be reduced by about 25% between 2013 and 2025 through the application of engine and transmission-related technologies alone (FEV, 2016; Meszler et al., 2016). Technology improvements taken into consideration for these 2016 studies include stronger downsizing of the engine, in combination with two-stage turbo charging; reducing friction losses; recirculating cooled exhaust gas; switching to the Miller combustion process; using a variable oil pump; improving fuel injection systems; and applying a seven-speed dual clutch transmission. For the WLTP, applying the same technologies, the 2016 studies estimated a lower CO_2 reduction potential of around 15%–20%. Manufacturers have already implemented part of this CO_2 reduction potential in the new vehicle fleet between 2013 and 2020. A recent assessment by AVL estimates a remaining CO_2 potential of about 10%, relative to a 2020 baseline and in WLTP, again relying on similar technologies, such as the continued development and application of the Miller combustion process, variable turbine geometry, cooled low-pressure exhaust gas recirculation, improved energy management, and friction reduction (AVL, 2020).[3]

For this analysis, we estimate a 1.6% per annum (p.a.) reduction of the WLTP CO_2 values to be available for the 2021–2025 timeframe. For the post-2025 timeframe, we assume that manufacturers will increasingly devote their research and development resources toward hybridization and electrification of new vehicles and explore no further improvement of the non-hybrid gasoline ICE powertrain in this analysis. Based on AVL data, the associated increase in direct manufacturing costs for the gasoline powertrain is estimated at a level of approximately €300 per vehicle by 2025, slightly decreasing in the years thereafter.

Our analysis does not take **diesel technology** into consideration, given the intention of several manufacturers to stop investing in the further development of passenger car diesel engines and the precipitous decline in Europe's diesel market share, which dropped from 49% in 2016 to 29% in 2020 (Mock et al., 2021).

In addition to powertrain improvements, vehicle **driving resistance** can be further optimized by designing lighter vehicles with a lower mass and improved aerodynamics, and by making use of lower resistance tires. An earlier assessment estimated the CO_2 reduction potential for all three measures combined to be 10%–20% by 2025, relative to a 2013 baseline and in NEDC terms (Kühlwein, 2016). This reduction equates to about 0.9%–1.9% p.a. A recent assessment by AVL includes road load reduction packages that reduce CO_2 emissions by 8%–16%, relative to a 2020 baseline and in WLTP terms (AVL, 2020). For the analysis, the available road load reduction potential of WLTP CO_2 values is assumed to be 0.9% p.a. between 2021 and 2030. As less expensive road load reduction technologies penetrate the fleet, potential additional reductions become more constrained and more expensive; we assume additional road load technology application will contribute an annual WLTP CO_2 reduction of just 0.4% for the 2030–2035 timeframe. We expect an associated increase of about €100 in direct manufacturing costs in the early years, increasing to about €300 by 2035.

3 Whereas the 2016 study applied a 2013 baseline vehicle equipped with a 1.8-liter (L) naturally aspirated multi-point fuel injection four-cylinder engine with a manual five-speed transmission, the AVL 2020 study starts off from a downsized 1.4-L single-stage turbo engine with a seven-speed dual clutch transmission.

Mild hybrid electric vehicles (MHEVs) can further reduce CO_2 emissions from an ICE. Most mild hybrid systems consist of a belt-driven starter generator and a 48-volt (V) lithium-ion battery. In a P0 configuration, the electric engine connects with the ICE through a belt on the front-end accessory drive, allowing for recuperation of braking energy and short-period power-boosting during acceleration phases. In addition, it is possible to decouple the transmission from the ICE and allow sailing when, for example, approaching a red traffic light. A previous ICCT paper estimated the CO_2 reduction potential of MHEV systems to be 10%–15% in NEDC terms (Isenstadt et al., 2016). These estimates are confirmed by recent AVL estimates of around 9% for a P0 MHEV system in WLTP terms, relative to a more efficient ICE baseline (AVL, 2020). Additional manufacturing costs in 2021 are about €640, relative to the baseline ICE with powertrain and road load improvements only.

In comparison to the 48-V technology, a **full hybrid electric vehicle (HEV)** is built with a battery with larger capacity and higher voltage. This setup allows for greater braking energy recuperation, longer range electric driving, and dedicated hybrid engines designed for higher efficiency in a narrow operating range. Relative to the 2020 baseline vehicle used for this analysis, a P2 HEV configuration reduces CO_2 emissions by about 20% in WLTP driving conditions (AVL, 2020). AVL forecasts additional potential to increase the efficiency of the HEV and therefore decrease air pollutant emissions as part of a "Zero Impact Emission" technology package that would achieve a CO_2 reduction of about 38%. However, these CO_2 reductions substantially increase manufacturing costs to as much as €1,500 –€2,400, depending on the configuration, relative only to the baseline ICE with powertrain and road load improvements. For the following analysis, we consider only a HEV P2 base configuration at the lowest available cost.

PLUG-IN HYBRID ELECTRIC VEHICLES (PHEVS)

In contrast to MHEVs, PHEVs allow for external battery charging via a plug. PHEVs can be driven in a predominantly electric 'charge-depleting' mode and a combustion engine 'charge-sustaining' mode. Since a combustion engine supports the electric motor in charge-depleting mode, this mode is not purely electric. In WLTP, PHEVs are assumed to start each driving day with a fully charged battery and in charge-depleting mode as long as the battery allows, then continue in charge-sustaining mode. The CO_2 and fuel consumption values of the two drive modes are weighted by an assumed charge-depleting mode drive share, referred to as the utility factor (UF). Differing from NEDC, the UF in WLTP is a function of the charge-depleting mode drive share, not the electric drive share. For a typical C-segment PHEV model with a WLTP charge-depleting mode range of about 50 km, the WLTP UF is 0.755. This analysis also takes into consideration PHEV models with higher WLTP charge-depleting mode ranges of 75 km and 100 km, which correspond to WLTP UFs of 0.852 and 0.902, respectively. Table 1 displays this report's key assumptions for PHEV technology.

During real-world usage, the fuel consumption and thus tailpipe CO_2 emissions of PHEVs are found to be 2–4 times higher than considered in WLTP (Plötz et al., 2020). This gap mainly results from a lower charging frequency than assumed in type-approval, a lower charge-depleting mode range, and higher fuel consumption in charge-sustaining mode.

The combined cost of the combustion engine and electric engine system for a PHEV is high relative to either ICE or electric costs alone. For the battery pack cost of PHEVs, a level of 181 €/kWh–196 €/kWh is assumed for 2021, going down to 81 €/kWh–88 €/kWh by 2035. We derive these estimates from an earlier ICCT paper (Lutsey & Nicholas, 2019). The total additional manufacturing cost for a PHEV-50 km are estimated in 2021 initially to be about €4,700 above those of an ICE with powertrain and road load improvements, decreasing to about €3,400 by 2035. For a PHEV-100 km variant, additional manufacturing cost decrease from €6,500 initially to €4,200 by 2035.

Table 1. Summary of key assumptions for PHEV technology.

	2021	2025	2030	2035
PHEV-50 km				
Utility factor (WLTP)	0.755	0.689	0.689	0.689
Energy consumption (WLTP)	0.15 kWh/km	0.14 kWh/km	0.14 kWh/km	0.13 kWh/km
Fuel consumption (WLTP)	1.5 L/100km	1.3 L/100km	1.3 L/100km	1.3 L/100km
Battery pack cost	196 €/kWh	147 €/kWh	102 €/kWh	88 €/kWh
Battery size	11 kWh	11 kWh	11 kWh	10 kWh
PHEV-75 km				
Utility factor (WLTP)	0.852	0.852	0.852	0.852
Energy consumption (WLTP)	0.16 kWh/km	0.16 kWh/km	0.15 kWh/km	0.15 kWh/km
Fuel consumption (WLTP)	0.9 L/100km	0.8 L/100km	0.8 L/100km	0.7 L/100km
Battery pack cost	188 €/kWh	141 €/kWh	98 €/kWh	84 €/kWh
Battery size	17 kWh	16 kWh	16 kWh	16 kWh
PHEV-100 km				
Utility factor (WLTP)	0.902	0.902	0.902	0.902
Energy consumption (WLTP)	0.17 kWh/km	0.16 kWh/km	0.16 kWh/km	0.16 kWh/km
Fuel consumption (WLTP)	0.6 L/100km	0.5 L/100km	0.5 L/100km	0.5 L/100km
Battery pack cost	181 €/kWh	136 €/kWh	95 €/kWh	81 €/kWh
Battery size	23 kWh	22 kWh	21 kWh	21 kWh

BATTERY ELECTRIC VEHICLES (BEVS)

Our analysis takes into consideration BEVs with an electric range of 350 km, 450 km, and 550 km. The WLTP energy consumption of all BEV types is considered with 0.16 kWh/km, including charging losses, as required under the test procedure (Table 2). Battery pack sizes vary initially between 52 kWh and 85 kWh. We again derive all estimates from an earlier ICCT paper (Lutsey & Nicholas, 2019) and use these estimates to extrapolate for the years 2030–2035.[4] The total additional manufacturing costs for a BEV-350 km are estimated in 2021 to start about €5,000 above those of an ICE with powertrain and road load improvements, decreasing to a level of about €750 above the ICE vehicle by 2035. For a BEV-550 km, costs decrease from about €9,000 in 2021 to €2,400 by 2035.[5]

Table 2. Summary of key assumptions for BEV technology.

	2021	2025	2030	2035
BEV-350km				
Energy consumption (WLTP)	0.16 kWh/km	0.15 kWh/km	0.15 kWh/km	0.15 kWh/km
Battery pack cost	141 €/kWh	105 €/kWh	73 €/kWh	63 €/kWh
Battery size[a]	52 kWh	51 kWh	49 kWh	48 kWh
BEV-450km				
Energy consumption (WLTP)	0.16 kWh/km	0.15 kWh/km	0.15 kWh/km	0.15 kWh/km
Battery pack cost	141 €/kWh	104 €/kWh	73 €/kWh	63 €/kWh
Battery size	68 kWh	66 kWh	64 kWh	62 kWh
BEV-550km				
Energy consumption (WLTP)	0.16 kWh/km	0.15 kWh/km	0.15 kWh/km	0.15 kWh/km
Battery pack cost	139 €/kWh	104 €/kWh	73 €/kWh	62 €/kWh
Battery size	85 kWh	83 kWh	80 kWh	78 kWh

[a] The required useable battery capacity is calculated from the energy consumption values without charging losses. These values are lower than WLTP values.

4 For the central case scenario, we assume direct manufacturing costs for batteries will decrease by 7% p.a. until 2030, with the annual rate of reduction gradually slowing to 1% p.a. by 2035.

5 For the baseline ICE vehicle, we use cost calculations from Lutsey & Nicholas (2019) scaled for an average European C-segment vehicle. We estimate 2018 powertrain costs for the European baseline ICE vehicle at €3,947, non-powertrain costs at €9,983, and indirect costs at €2,855. Other cost elements include vehicle manufacturer and dealer distribution costs and profits that we estimate at €6,653.

FUEL CELL VEHICLES (FCVS)

Today, only a handful of FCV models are available on the market, with negligible sales figures. Thus, we only take FCVs into account for 2030 and beyond, and only for a sensitivity analysis. Unlike for BEVs, the fuel efficiency and cost of a FCV varies only marginally with driving range. We consider a FCV with a driving range of 450 km and assume hydrogen consumption to be 0.8 kg/100 km in 2021, improving to a level of 0.7 kg/100 km by 2035. The most expensive components of a FCV today and in the foreseeable future is its fuel cell stack and, to a lesser degree, the hydrogen storage tank. For both components, we derive expected costs from AVL (2020), extrapolate to 2035, and assume a production volume of 0.5 million FCVs per year in 2030. For the remaining electric components, we apply the same costs as for BEVs, Resulting in additional manufacturing costs equivalent in 2030 to that of a BEV with a driving range of 550 km, and about €1,000 higher than for a 450 km-range BEV. Given the very low production volumes to date, the future cost of FCVs strongly depend on future technical progress and production volumes: Assumptions for the future cost of FCVs carry greater uncertainty than assumptions for BEVs.

TECHNOLOGIES IN COMPARISON

Table 3 and Table 4 summarize the technology input data from a WLTP CO_2 emission value and a direct manufacturing cost viewpoint. The average WLTP CO_2 emission level for the 2021 baseline ICE vehicle is set at 143 g/km. From there, it is possible to reduce emissions by adding technology packages and transitioning to more advanced technologies. All vehicle types that use ICE technology therefore allow for an initial annual WLTP CO_2 reduction assumption of about 2.7%, slowing down in later years to just 0.4%-p.a. further ICE improvement from 2030 onwards. All ICE vehicle types are subject to an increase in cost over the years to accommodate for improvements in powertrain technology and reduced road load. Relative to the total manufacturing cost for the 2018 baseline vehicle, estimated at €18,000 based on Díaz et al. (2020), the initial increase in cost is low, at a maximum of 0.4% p.a. In contrast, BEVs are subject to a notable cost decrease of 2.5%–4.5% p.a. in early years.

Table 3. WLTP CO_2 emission levels, by vehicle type, for the years 2021–2035, plus average annual improvements

		CO_2 (WLTP, in g/km)				CO_2 (WLTP, per year)		
		2021	2025	2030	2035	2021-25	2025-30	2030-35
ICE	Powertrain improvements only	143	135	134	134	-1.6%	-0.1%	0.0%
	+ road load improvements	141	127	120	118	-2.7%	-1.0%	-0.4%
ICE_MHEV	P0 mild hybrid	128	115	109	107	-2.7%	-1.0%	-0.4%
ICE_HEV	P2 full hybrid	114	102	97	95	-2.6%	-1.1%	-0.4%
PHEV	Plug-in hybrid (50 km electric range)	35	31	30	29	-3.0%	-0.7%	-0.7%
	“ (75 km)	21	19	18	17	-2.7%	-1.0%	-0.4%
	“ (100 km)	14	12	12	12	-2.8%	-0.9%	-0.4%
BEV	Battery Electric Vehicle (350 km electric range)	0				n/a		
	“ (450 km)							
	“ (550 km)							
FCV	Fuel Cell Vehicle (450 km electric range)			0		n/a		

Table 4. Direct manufacturing cost increase, by vehicle type, for the years 2021–2035 relative to a 2018 baseline vehicle.

		2021	2025	2030	2035	per year		
						2021-25	2025-30	2030-35
ICE	Powertrain improvements only	100 €	270 €	270 €	260 €	0.2%	0.0%	0.0%
	+ road load improvements	140 €	410 €	540 €	600 €	0.4%	0.1%	0.1%
ICE_MHEV	P0 mild hybrid	780 €	1,010 €	1,110 €	1,150 €	0.3%	0.1%	0.0%
ICE_HEV	P2 full hybrid	1,640 €	1,830 €	1,890 €	1,910 €	0.3%	0.1%	0.0%
PHEV	Plug-in hybrid (50 km electric range)	4,850 €	4,470 €	3,960 €	3,650 €	-0.5%	-0.6%	-0.3%
	“ (75 km)	5,760 €	5,030 €	4,350 €	4,060 €	-1.0%	-0.8%	-0.3%
	“ (100 km)	6,610 €	5,680 €	4,730 €	4,380 €	-1.3%	-1.1%	-0.4%
BEV	Battery Electric Vehicle (350 km electric range)	5,210 €	3,400 €	1,840 €	1,340 €	-2.6%	-1.8%	-0.6%
	“ (450 km)	7,170 €	4,770 €	2,790 €	2,150 €	-3.5%	-2.3%	-0.7%
	“ (550 km)	9,170 €	6,280 €	3,790 €	2,960 €	-4.3%	-2.9%	-0.9%
FCV	Fuel Cell Vehicle (450 km electric range)	7,260 €		3,800 €	2,920 €	-12.1%		-1.0%

Note. Costs include the average annual cost increase or reduction relative to the estimated total manufacturing cost for the 2018 baseline vehicle, excluding any profits and taxes.

Retail price reductions are much more pronounced than direct manufacturing cost reductions for electric vehicles (Table 5). In addition to direct manufacturing costs, retail price also accounts for indirect cost elements, such as research and development and warranty costs. While indirect costs for electric vehicles are initially spread across a low number of vehicles produced, they are distributed across a much larger sales volume in later years and can even drop below those of conventional ICE vehicles. An earlier ICCT paper estimated the indirect cost decrease for BEVs at about 70% from 2017–2025 (Lutsey & Nicholas, 2019); for this paper, we assume an indirect cost reduction of 80% between 2017 and 2030, with indirect costs remaining constant after 2030. As a result, we expect the retail price of BEVs to decrease by about 3%–8% p.a. between 2021 and 2025, driven by battery cost reductions and declining indirect costs. From 2030 onwards, the annual reduction in retail price is only about 1%, reflecting minor continuing improvements in battery technology and reductions in price but no further indirect cost reduction.

Table 5. Retail price increase, by vehicle type, for the years 2021–2035. relative to a 2018 baseline vehicle.

		2021	2025	2030	2035	per year		
						2021-25	2025-30	2030-35
ICE	Powertrain improvements only	150 €	350 €	360 €	340 €	0.2%	0.0%	0.0%
	+ road load improvements	200 €	530 €	710 €	790 €	0.3%	0.1%	0.1%
ICE_MHEV	P0 mild hybrid	1,090 €	1,320 €	1,460 €	1,510 €	0.2%	0.1%	0.0%
ICE_HEV	P2 full hybrid	2,300 €	2,390 €	2,470 €	2,490 €	0.1%	0.1%	0.0%
PHEV	Plug-in hybrid (50 km electric range)	6,790 €	6,210 €	5,490 €	5,060 €	-0.6%	-0.6%	-0.3%
	“ (75 km)	8,050 €	7,000 €	6,040 €	5,630 €	-1.1%	-0.8%	-0.3%
	“ (100 km)	9,240 €	7,900 €	6,570 €	6,070 €	-1.4%	-1.1%	-0.4%
BEV	Battery Electric Vehicle (350 km electric range)	10,260 €	4,590 €	1,180 €	480 €	-6.2%	-2.9%	-0.6%
	“ (450 km)	13,000 €	6,510 €	2,510 €	1,610 €	-7.2%	-3.4%	-0.7%
	“ (550 km)	15,790 €	8,620 €	3,920 €	2,740 €	-8.0%	-4.0%	-1.0%
FCV	Fuel Cell Vehicle (450 km electric range)			3,920 €	2,690 €			-1.0%

Note. Costs include the average annual cost increase or reduction relative to the estimated retail price for the 2018 baseline vehicle.

Figure 1 illustrates the retail price development of the various vehicle technologies over time. All prices shown reflect the theoretical potential available for each technology from today’s perspective and assume mass production volumes. The figure does not allow for any conclusions about how individual technologies phase in or out of the market over time.[6] Furthermore, we assume that all manufacturing cost increases are passed onto the consumer, and we do not apply a continuous reduction in baseline vehicle costs.

Prices increase slightly for ICEs, while BEV prices drop quickly: A BEV-350 km reaches parity with a conventional ICE vehicle by about 2031. MHEVs reach price parity about two years earlier. Hybrid engine vehicles, particularly PHEVs, remain significantly more expensive in comparison to a conventional ICE or MHEV. In comparison to BEVs, PHEVs are cheaper in earlier years, but that cost advantage disappears by 2024 as BEV prices decline.

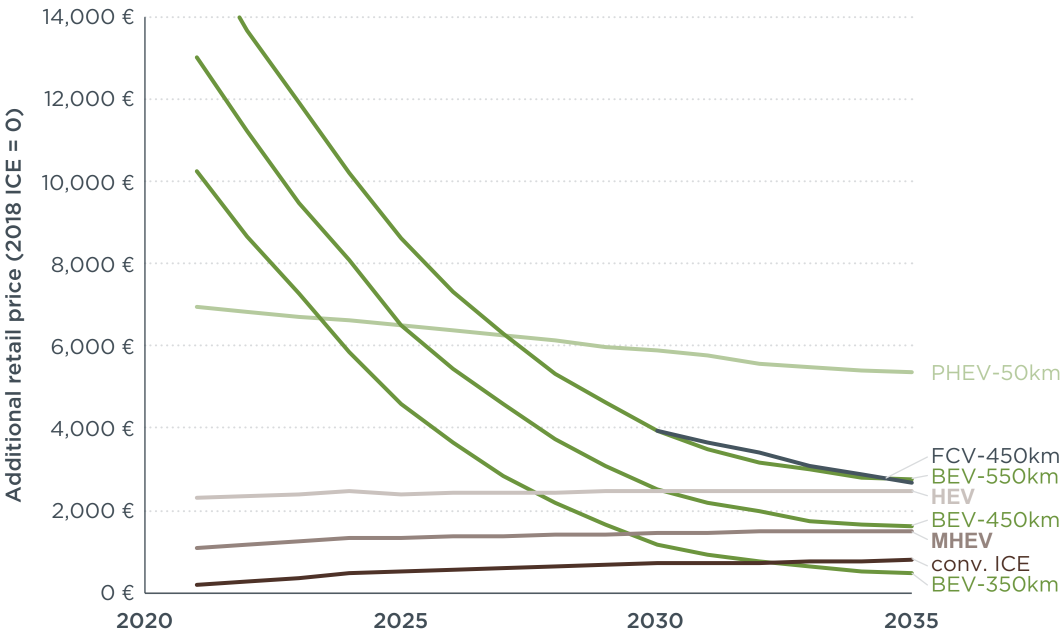

Figure 1. Illustration of assumed retail price developments for various vehicle types relative to a 2018 baseline vehicle.

6 For example, the comparison between additional retail prices for a conventional ICE and a BEV in 2031 can be misleading, as a conventional ICE is unlikely to be available in the market by that year and will likely be replaced by, for instance, a MHEV. Technology market penetration is subject to the scenario analysis later in the paper.

CREDITS AND OTHER ADJUSTMENTS

In addition to deploying more advanced technologies, for compliance purposes, vehicle manufacturers can also reduce the WLTP CO_2 level of their fleet by making use of regulatory credits. We briefly describe the assumed effect of these credits and other adjustments in the following section.

PHASE-IN

When determining whether a vehicle manufacturer complied with its fleet-average WLTP CO_2 target in 2020, 5% of its vehicles registered with the highest CO_2 emission levels are left out of the calculation by the authorities, effectively reducing the average fleet emission level on paper and simplifying compliance with the regulation. However, as this phase-in provision, with an estimated impact of 3 g CO_2/km (Mock et al., 2021), only applies in 2020 and is of no relevance for any future years, it is disregarded for the analysis.

POOLING

For compliance purposes, a manufacturer can choose to collaborate with other manufacturers by forming a manufacturer pool. In this case, the average CO_2 emission level is calculated by taking into account the vehicle fleet of all members of the pool. If one manufacturer has a lower fleet average CO_2 level than the other manufacturer(s), it may ask for financial compensation for joining a pool, such as when Tesla joined a pool with FCA in 2019, helping FCA reduce its fleet average CO_2 level in return for a financial transaction. As this analysis focuses on compliance cost for an average European vehicle, it inherently accounts for the effect of pooling, ensuring that the most cost-effective approach for reaching CO_2 reductions is achievable.

CHANGES IN REGIONAL SCOPE

The CO_2 standards for new vehicles not only apply to the EU, but may also cover all new vehicles registered in the EEA. In addition to the EU Member States, the EEA includes Iceland, Liechtenstein, and Norway. While these three countries had not yet adopted the regulation into national law by 2018 (the baseline year for this analysis), Iceland and Norway have now done so and will be part of the assessment of compliance with the 2020/21 CO_2 targets as well as future post-2021 standards. Despite its relatively low market size of about 150,000 new cars per year, Norway's high share of electric vehicles (about 70% of new passenger car registrations in 2020) notably reduces the EU-wide fleet average CO_2 emission level by approximately 0.7 g/km (in WLTP terms). It thereby helps manufacturers to comply with the regulation at zero additional cost, a one-time effect that this analysis takes into account. Meanwhile, the United Kingdom (UK) leaving the EU and current exclusion from the EEA also affects fleet average CO_2 emission levels. However, as the UK's average new car CO_2 level (127 g/km vs. 122 g/km in 2019) and electric vehicle market share (11% for 2020) is very similar to the average EU level, the effect is likely negligible (Díaz et al., 2020; Mock et al., 2021), we did not apply an adjustment for this analysis.

ZERO- AND LOW-EMISSION VEHICLES

As part of the European CO_2 standards for passenger cars, many electric vehicles benefit from multipliers that leverage their benefit for manufacturers' compliance strategy. Between 2020 and 2022, every car with type-approval CO_2 emissions of less than 50 g/km will count more toward meeting the fleet average than cars with emissions above that cutoff. The weighting factors are: 2.00 (2020), 1.67 (2021), and 1.33 (2022). The limit for the use of these so-called super-credits, expressed as the difference between average new fleet type-approval CO_2 emissions values calculated with and without the application of super-credits, is set at a maximum of 7.5 g/km for the three years 2020–2022 combined. By the end of 2020, the majority of manufacturers—with the exception of the Toyota-Mazda pool—had already exhausted or was close to exhausting their maximum super-credits (Mock et al., 2021).

For 2025 and 2030, the regulation defines non-binding benchmarks (i.e., targets) for the market share of zero- and low-emission vehicles (ZLEVs): 15% for 2025 and 35% for 2030. If a manufacturer exceeds the minimum ZLEV market share, its CO_2 target is relaxed by up to 5%. Any vehicle with a WLTP CO_2 emission level of 50 g/km or less qualifies as a ZLEV, and PHEVs and electric vehicles equipped with a combustion engine range extender are partially counted as ZLEVs. Also, ZLEVs first registered in the 14 EU Member States that had a below-average electric vehicle share in 2017 are valued higher for compliance purposes (Mock, 2019). Based on market data, the 2020 European weighted ZLEV share would have been about 9%, compared to an unweighted ZLEV share of 11% (Mock et al., 2021). This ZLEV share is already approaching the 2025 ZLEV benchmark of 15%, with five more years remaining. Against this background, and given that several vehicle manufacturers have already announced 2030 electric vehicle market shares higher than the current 2030 ZLEV target (Wappelhorst, 2020), we assume in this analysis that the average manufacturer will exceed the ZLEV target shares and will benefit from a reduced stringency of 5% for CO_2 fleet targets.

ECO-INNOVATIONS

Some technologies can help to reduce vehicle CO_2 emissions during real-world driving but are only partially reflected or excluded when determining emission levels during the official laboratory test procedure. To incentivize the use of such technologies, the European CO_2 regulation provides credits for eco-innovations, also called off-cycle technologies in other markets. Until recently, eco-innovations did not have a large effect on fleet average emission levels. In 2019, the average eco-innovation credit per manufacturer was 0.2 g/km (NEDC), with a spread between zero (for VW Group) and 0.9 g/km (for BMW) (Tietge et al., 2020). Meanwhile, vehicle manufacturers and parts suppliers have successfully registered several eco-innovation technologies, such as a solar roof, an efficient alternator, and a coasting function, applicable under NEDC (European Commission, 2021a). While few eco-innovations have been approved so far with WLTP, given the relatively low cost of most of these technologies, we expect an increase in the share of vehicles equipped with eco-innovation technologies under WLTP.

The maximum credit from eco-innovations for a manufacturer is capped at 7 g/km. For this analysis, we assume that manufacturers will deploy eco-innovation technologies initially worth a credit of 1 g/km in WLTP from 2020 onwards, increasing to 3 g/km in later years. We assume no eco-innovation credits are deployed for electric vehicles (BEVs and FCVs). As a result, with an increasing share of electric vehicles, the effect of the eco-innovations provision is expected to diminish. We derived cost estimates from a 2015 Ricardo-AEA report for the European Commission (Hill et al., 2016), following the same methodology explained in a 2016 ICCT report (Meszler et al., 2016). The resulting direct manufacturing cost for the assumed 5 g/km eco-innovation credit is on the order of €15.

TEST PROCEDURE OPTIMIZATION

Between 2001 and 2018, the gap between official type-approval CO_2 emission levels, as measured in NEDC, and average real-world values increased from about 8% to 40% (Tietge et al., 2019). In the first year of the introduction of the WLTP, type-approval CO_2 emission levels of new cars increased by a factor of 1.21 in 2018, on average (Dornoff et al., 2020). We use this factor to convert NEDC to WLTP CO_2 values in this analysis. As a result of the increase in type-approval CO_2 emission levels, the average real-world gap dropped to a level of about 14%. However, as described in a 2015 report for the UK Committee on Climate Change (Stewart et al., 2015) and a 2020 ICCT report (Dornoff et al., 2020), the average real-world gap is likely to increase again in future years. The underlying reason for this increase is that while vehicle manufacturers have an incentive to inflate the WLTP-NEDC CO_2 ratio until 2020, from 2021 onwards it will benefit them to decrease WLTP CO_2 values. In this analysis, for those scenarios with a higher regulatory pressure (the Moderate and Higher Ambition scenarios), we assume that this test procedure optimization will result in a 1%-p.a. CO_2 decrease on paper for all ICEs at virtually no cost beginning in 2021. We cap this effect at a total 5% CO_2 decrease in 2025, because we assume for these two scenarios that by 2025, the European Commission will have combined the monitoring of real-world CO_2 emission levels via on-board fuel consumption meters (Dornoff, 2019) with a sanctioning mechanism that will effectively disincentivize vehicle manufacturers from further gaming the WLTP type-approval system. For the scenario with lower regulatory pressure (the Lower Ambition scenario), we assume the same test procedure optimization will take place, but between 2025 and 2030.

TECHNOLOGY CO-BENEFITS

Several technologies considered for the analysis not only provide a reduction in CO_2 emission levels, but also offer noteworthy co-benefits for consumers and society. For example, hybrid and full electric vehicles boost low-end torque performance, which most drivers consider an attractive benefit. From a societal perspective, reduced air pollution and noise pollution from electric vehicles are important technology co-benefits in addition to a reduction in CO_2 emission levels. As explained in an earlier ICCT report (Meszler et al., 2016), for regulatory purposes it is reasonable to discount such co-benefits instead of attributing the full technology cost to reductions in CO_2 emission levels. Nevertheless, this analysis disregards technology co-benefits to ensure a conservative estimate of future compliance cost.

POST-EURO 6 AIR POLLUTANT EMISSION STANDARD

The European Commission is currently facilitating expert discussions around the introduction of an air pollution emission standard to succeed the current Euro 6 regulation, key aspects of which are summarized in a 2019 ICCT report (Rodríguez et al., 2019). While the discussions are ongoing, we assume in this analysis that from 2025 onwards, the EU will require new ICEs and PHEVs to be equipped with an advanced exhaust aftertreatment system in order to comply with a Euro 7 emission standard. We assume the stringency of that standard will be similar to the US Tier 3 emission standard, which has applied to North America from 2017 onwards. For a cost estimate, we compare data from OMEGA for a Tier 3 technology package with AVL's dedicated hybrid engine technology package, which includes a Euro 7 emissions and performance package. We arrive at an estimated Euro 7 direct manufacturing compliance cost for gasoline vehicles of about €125 per vehicle in 2025. Learning curve factors are also derived from OMEGA, resulting in a slight decrease in direct manufacturing costs to a level of about €115 by 2035. Any effect on WLTP CO_2 emission levels is implicitly included in the CO_2 reduction technology assumptions.

SYNTHETIC FUELS

Some members of the automotive and oil industries promote embedding a crediting system for “renewable and carbon-neutral” fuels into the passenger car CO_2 fleet standards; see Bosch (2020) for an example. Biofuels, derived from food and waste-based sources, constitute one category of these fuels. However, in light of sustainability concerns surrounding indirect land use change, the European Commission capped the contribution of food-based fuels toward the renewable energy in transport targets in the Renewable Energy Directive to 7% of road and rail transport fuel for 2020 consumption levels in each member state (European Union, 2018). The use of wastes and residues for use in biofuels is also limited (Searle & Malins, 2016). Synthetic fuels, which include but are not limited to electrofuels (also known as eFuels or power-to-liquids), make up the second category of synthetic fuels. eFuels are derived via electrolysis from water by adding CO_2. eFuels produced solely with low-carbon renewable energy from sources such as wind or solar could have very low carbon content. However, eFuels are energy inefficient, with approximately 50% of available fuel energy “lost” during the fuel production process, compared with about 10% lost when generating and using electricity to drive an electric vehicle (Searle, 2020). Mostly due to their low energy efficiency, the production cost of eFuels is likely to remain high and is expected to decrease only marginally in future years.

Even assuming a subsidy as high as €3 per liter (L) of diesel equivalent of eFuel, it is estimated that investments will only be sufficient to provide about 4.5 billion L of gasoline equivalent fuel in the EU by 2035 (Searle and Christensen, 2018). With an expected total fuel demand of 212 billion L by 2035 (European Union, 2016), this amount corresponds to approximately 2% of conventional fuel that eFuels could potentially replace by 2035. This percentage not only assumes a financial subsidy more than twice that of today’s total fuel price, but it also assumes that 100% of the available eFuel would be used in passenger cars to the exclusion of all other potential uses, such as in airplanes. Permitting the crediting of eFuels in the CO_2 fleet standards regulation would essentially allow vehicle manufacturers to deploy less-efficient technology while paying fuel providers to increase the production volume of eFuels flowing into the EU market. If vehicle manufacturers were to pay the full amount of required eFuel subsidy that we assume at €3/L, the cost per gram of CO_2 reduced per kilometer (g CO_2/km) would equal about €160, assuming a vehicle lifetime mileage of 230,000 km and discounting future costs—an amount significantly higher than the €95 per g CO_2/km penalty foreseen for non-compliance with the regulation. The cost of the eFuel subsidies would be lower for the vehicle manufacturer if Member State governments bore part of it, but the cost would still apply from a societal perspective. For this analysis, an eFuels potential of replacing 2% of conventional fuel by 2035 is applied only in a sensitivity scenario.

Table 6 summarizes credits and other adjustments taken into account for the scenarios.

Table 6. Summary of the assumed impact of credits and other adjustments on CO_2 emission levels and costs, relative to a 2018 baseline.

Credit	2020	2025	2030	2035
Phase-in	-3 g/km, €0	n/a		
Pooling	n/a			
Norway	-0.7 g/km (vs. 2018), €0			
Super-credits	-7 g/km, €0	n/a		
ZLEVs	n/a	-5% (~4 g/km) €0	-5% (~3 g/km) €0	n/a
Eco-innovations	up to -3 g/km, €15			
Test procedure	n/a	up to -5% (~4 g/km), €0		n/a
Co-benefits	n/a			
Post Euro 6	n/a	€125	€120	€115
Synthetic fuels (only for sensitivity analysis)	n/a	n/a	-1% (~1 g/km) €160	-2% (~2 g/km) €320

SCENARIOS

We consider four main scenarios to represent the potential future development of the European passenger car vehicle market. The definitions of the four scenarios align with an earlier ICCT paper that studied the impact of standards on GHG emission levels of the transport sector and the entire EU economy (Buysse et al., 2021).

ADOPTED POLICIES

In the Adopted Policies scenario, the share of both BEVs and PHEVs increases from 7% in 2021 to 14% in 2025, and to 27% in 2030 (Table 7). Without a strengthened EU regulation, no further uptake of BEVs and no further technical progress is assumed beyond 2030. In the absence of a stringent real-world enforcement mechanism, we assume that for the majority of PHEVs, the charge-depleting range remains at about today's average level of 50 km (WLTP). Improvements in batteries and electric motors and a shift toward PHEVs with a higher electric range moderately decrease the average WLTP CO_2 emission level for PHEVs from 35 g/km in 2021 to 31 g/km in 2025 and 29 g/km in 2030. Note that in real-world usage, the tailpipe CO_2 emissions of PHEV are found to be two to four times higher. Under the current regulation, PHEVs count as ZLEVs, although only partially. As a result, while the unweighted ZLEV share increases from 14% in 2021 to 27% in 2025 and 53% in 2030, the weighted ZLEV share reaches 20% in 2025 and 40% in 2030. It is assumed that manufacturers will strive towards these ZLEV levels in order to ensure that the ZLEV benchmark targets are exceeded by five percentage points as required to make full use of the 5% relaxation of the CO_2 fleet targets. With manufacturers deploying electric vehicles to fully exploit the ZLEV benchmark targets, the remaining required technical progress for combustion engine vehicles turns out to be zero. The share of MHEV vehicles decreases from 20% in 2021 to zero by 2025 onwards, as targets can be met without the application of the technology. Similarly, the share of HEVs goes from 5% in 2021 to 2% by 2025 and beyond. Overall, the average WLTP CO_2 emissions for all combustion engine vehicles (including MHEV and HEV) increases from 130 g/km in 2021 to 133 g/km in 2025 and 140 g/km in 2030. Excluding the effects of eco-innovation credits and test procedure optimization, the increase in ICE CO_2 emission levels is even stronger for the 2021-2025 time period. From 2031 onwards, with the assumed phase-out of the ZLEV credit, some combustion engine improvement is required, so that the average WLTP CO_2 level decreases slightly to 133 g/km. The Adopted Policies scenario ensures reaching the current EU regulatory targets of 15% lower WLTP CO_2 emission levels of the new passenger car fleet by 2025 and 37.5% lower by 2030, relative to a 2021 baseline.

Table 7. Summary of key characteristics of the ***Adopted Policies*** scenario.

	2021	2025	2030	2035
BEV share	7%	13.5%	26.5%	26.5%
BEV-350km	*7%*	*10.5%*	*14.5%*	*14.5%*
BEV-450km	*0%*	*2%*	*8%*	*8%*
BEV-550km	*0%*	*1%*	*4%*	*4%*
CO_2 (WLTP)	0 g/km	0 g/km	0 g/km	0 g/km
PHEV share	7%	13.5%	26.5%	26.5%
CO_2 (WLTP)	35 g/km	31 g/km	29 g/km	29 g/km
average progress (WLTP)	n/a	-2.7% p.a.	-1.1% p.a.	0% p.a.
ZLEV share: unweighted	14%	27%	53%	53%
weighted	10%	20%	40%	40%
HEV share	5%	2%	2%	2%
MHEV share	20%	0%	0%	0%
Non-hybrid ICE share	61%	71%	45%	45%
Total ICE share	86%	73%	47%	47%
CO_2 (WLTP)	130 g/km	133 g/km	140 g/km	133 g/km
average annual progress	n/a	+0.6% p.a.	+0.9% p.a.	-1.0% p.a.
excl. eco-innovation credits and test cycle optimization	*n/a*	*+2.4% p.a.*	*+0.9% p.a.*	*-1.0% p.a.*
New car CO_2 (WLTP)	115 g/km	98 g/km	72 g/km	72 g/km
excl. ZLEV credit	*n/a*	*103 g/km*	*76 g/km*	*n/a*
vs. 2021	n/a	**-15%**	**-37.5%**	**-37.5%**

LOWER AMBITION

For the Lower Ambition scenario, we assume that the fleet average WLTP CO_2 emission target for 2025 is strengthened from the current 15% reduction to 20% (Table 8). From 2021 to 2025, the fleet penetration assumptions for BEVs and PHEVs remain the same as in the Adopted Policies scenario and assume that manufacturers will deploy just enough ZLEVs to exploit fully the benchmark target credit, which is assumed to remain the same as in the Adopted Policies scenario. Even though the share of HEVs decreases slightly, manufacturers reach the 20% CO_2 reduction target assumed for 2025 because unlike in the Adopted Policies scenario, emission levels from combustion engine vehicles are not allowed to increase, and manufacturers are deploying more MHEVs, the new vehicle market share of which doubles from 20% in 2021 to 40% in 2025. For 2030, we assume that the EU fleet target will be strengthened from the current 37.5% reduction of WLTP CO_2 emissions to 50%. Manufacturers will reach this revised 2030 target by keeping BEV and PHEV shares identical to the Adopted Policies scenario—again, by maximizing the benefit of the ZLEV benchmark credit—and beginning in 2026, investing in the continuous improvement of road load coefficients for all vehicles and powertrain improvements for combustion engines. In addition, as the proportion of conventional ICEs declines in favor of MHEVs, the average CO_2 level of ICEs decreases to 112 g/km by 2030. These improvements of the WLTP CO_2 emission values of combustion engine vehicles continue at a rate of 2.4% p.a. until 2035. The share of ZLEVs increases to a level of 68%. However, while the share of BEVs increases to 56%, the share of PHEVs decreases to 13%. In sum, new car fleet WLTP CO_2 emissions decrease by 70% in 2035 compared to the 2021 baseline level.

Table 8. Summary of key characteristics of the **Lower Ambition** scenario.

	2021	2025	2030	2035
BEV share	7%	13.5%	26.5%	55.5%
BEV-350km	*7%*	*10.5%*	*14.5%*	*31%*
BEV-450km	*0%*	*2%*	*8%*	*18%*
BEV-550km	*0%*	*1%*	*4%*	*6.5%*
CO_2 (WLTP)	0 g/km	0 g/km	0 g/km	0 g/km
PHEV share	7%	13.5%	26.5%	12.5%
CO_2 (WLTP)	35 g/km	31 g/km	26 g/km	21 g/km
average progress (WLTP)	n/a	-2.7% p.a.	-3.4% p.a.	-3.8% p.a.
ZLEV share: unweighted	14%	27%	53%	68%
weighted	10%	20%	42%	64%
HEV share	5%	4%	0%	0%
MHEV share	20%	40%	30%	30%
Non-hybrid ICE share	61%	29%	17%	2%
Total ICE share	86%	73%	47%	32%
CO_2 (WLTP)	130 g/km	126 g/km	112 g/km	99 g/km
average annual progress	n/a	-0.9% p.a.	-2.2% p.a.	-2.4% p.a.
excl. eco-innovation credits and test cycle optimization	*n/a*	+0.9% p.a.	*-2.2% p.a.*	*-2.4% p.a.*
New car CO_2 (WLTP)	115 g/km	92 g/km	58 g/km	35 g/km
excl. ZLEV credit	*n/a*	*97 g/km*	*61 g/km*	*n/a*
vs. 2021	n/a	**-20%**	**-50%**	**-70%**

MODERATE AMBITION

For the Moderate Ambition scenario, we assume a full phase-out of combustion engine vehicles by 2035 (Table 9). In 2025, we apply an interim target of 30% lower WLTP CO_2 emissions compared to 2021, rising to 70% in 2030. Manufacturers reach the strengthened 2025 target with the same fleet mix as in the Lower Ambition scenario. However, unlike in the Lower Ambition scenario, manufacturers are now expected to invest fully in improvements in road load and powertrain from 2022 onwards, thereby exploiting much of the remaining expected ICE improvements by 2030. By assuming a more stringent real-world enforcement mechanism, the charge-depleting range of PHEVs is expected to increase, thereby reducing their average WLTP CO_2 emission level to 30 g/km by 2025. In real-world usage conditions, these levels are considered to remain several times higher. For 2030, the share of BEVs strongly increases to a level of 54%, while the share of PHEVs drops to 14%. By 2035, all new passenger cars registered are BEVs.

Table 9. Summary of key characteristics of the **Moderate Ambition** scenario.

	2021	2025	2030	2035
BEV share	7%	13.5%	54%	100%
BEV-350km	*7%*	*10.5%*	*28%*	*40%*
BEV-450km	*0%*	*2%*	*16%*	*40%*
BEV-550km	*0%*	*1%*	*10%*	*20%*
CO_2 (WLTP)	0 g/km	0 g/km	0 g/km	0 g/km
PHEV share	7%	13.5%	13.5%	0%
CO_2 (WLTP)	35 g/km	27 g/km	21 g/km	n/a
average progress (WLTP)	n/a	-5.1% p.a.	-4.9% p.a.	n/a
ZLEV share: unweighted	14%	27%	68%	100%
weighted	10%	21%	63%	100%
HEV share	5%	4%	0%	0%
MHEV share	20%	40%	32.5%	0%
Non-hybrid ICE share	61%	30%	0%	0%
Total ICE share	86%	74%	32.5%	0%
CO_2 (WLTP)	130 g/km	109 g/km	104 g/km	n/a
average annual progress	n/a	-3.9% p.a.	-0.9% p.a.	n/a
excl. eco-innovation credits and test cycle optimization	*n/a*	*-2.1% p.a.*	*-0.9% p.a.*	*n/a*
New car CO_2 (WLTP)	115 g/km	80 g/km	35 g/km	0 g/km
excl. ZLEV credit	*n/a*	*84 g/km*	*37 g/km*	*n/a*
vs. 2021	n/a	**-30%**	**-70%**	**-100%**

HIGHER AMBITION

In the Higher Ambition scenario, we assume the phase-out of combustion engines to occur by 2030, again relying completely on BEVs (Table 10). For 2025, we identify an interim target of 40% lower WLTP CO_2 emissions. To reach the 2025 target, manufacturers deploy 25% BEVs while retaining a PHEV share about constant with 2021. All conventional ICEs are replaced with MHEVs by 2025, resulting in an average ICE CO_2 emission level of 103 g/km. Between 2025 and 2030, the share of BEVs increases rapidly to 100%, while all other technologies are phased out of the market.

Table 10. Summary of key characteristics of the **Higher Ambition** scenario.

	2021	2025	2030	2035
BEV share	7%	25%	100%	100%
BEV-350km	*7%*	*16%*	*40%*	*40%*
BEV-450km	*0%*	*4%*	*40%*	*40%*
BEV-550km	*0%*	*5%*	*20%*	*20%*
CO_2 (WLTP)	0 g/km	0 g/km	0 g/km	0 g/km
PHEV share	7%	7%	0%	0%
CO_2 (WLTP)	35 g/km	27 g/km	n/a	n/a
average progress (WLTP)	n/a	-4.8% p.a.	n/a	n/a
ZLEV share: unweighted	14%	32%	100%	100%
weighted	10%	29%	100%	100%
HEV share	5%	4%	0%	0%
MHEV share	20%	64%	0%	0%
Non-hybrid ICE share	61%	0%	0%	0%
Total ICE share	86%	68%	0%	0%
CO_2 (WLTP)	130 g/km	103 g/km	n/a	n/a
average annual progress	n/a	-5.2% p.a.	n/a	n/a
excl. eco-innovation credits and test cycle optimization	*n/a*	*-3.4% p.a.*	*n/a*	*n/a*
New car CO_2 (WLTP)	115 g/km	69 g/km	0 g/km	0 g/km
excl. ZLEV credit	*n/a*	*72 g/km*	*n/a*	*n/a*
vs. 2021	n/a	**-40%**	**-100%**	**-100%**

Figure 2 and Figure 3 summarize the technology market share assumptions for the four main policy scenarios. BEVs account for about one quarter of the market between 2030 and 2035 in the Adopted Policies Scenario, increasing to about half of the market by 2035 in the Lower Ambition scenario. In the Moderate Ambition scenario, BEVs account for half of the market by 2030 and all of the market by 2035. In the Higher Ambition scenario, full BEV deployment accelerates to 2030. PHEVs play only a marginal role in the Moderate and Higher Ambition scenarios, with manufacturers focusing on full BEV deployment. In the Adopted Policies scenario, PHEVs comprise about one quarter of the market, declining to about 13% by 2035 in the Lower Ambition scenario. The share of HEVs remains very low in all four scenarios. MHEVs quickly displace conventional ICEs in all scenarios, except for the Adopted Policies scenario, where CO_2 reduction targets can be met solely by increasing the share of ZLEVs, and zero technical progress is required for combustion engine vehicles.

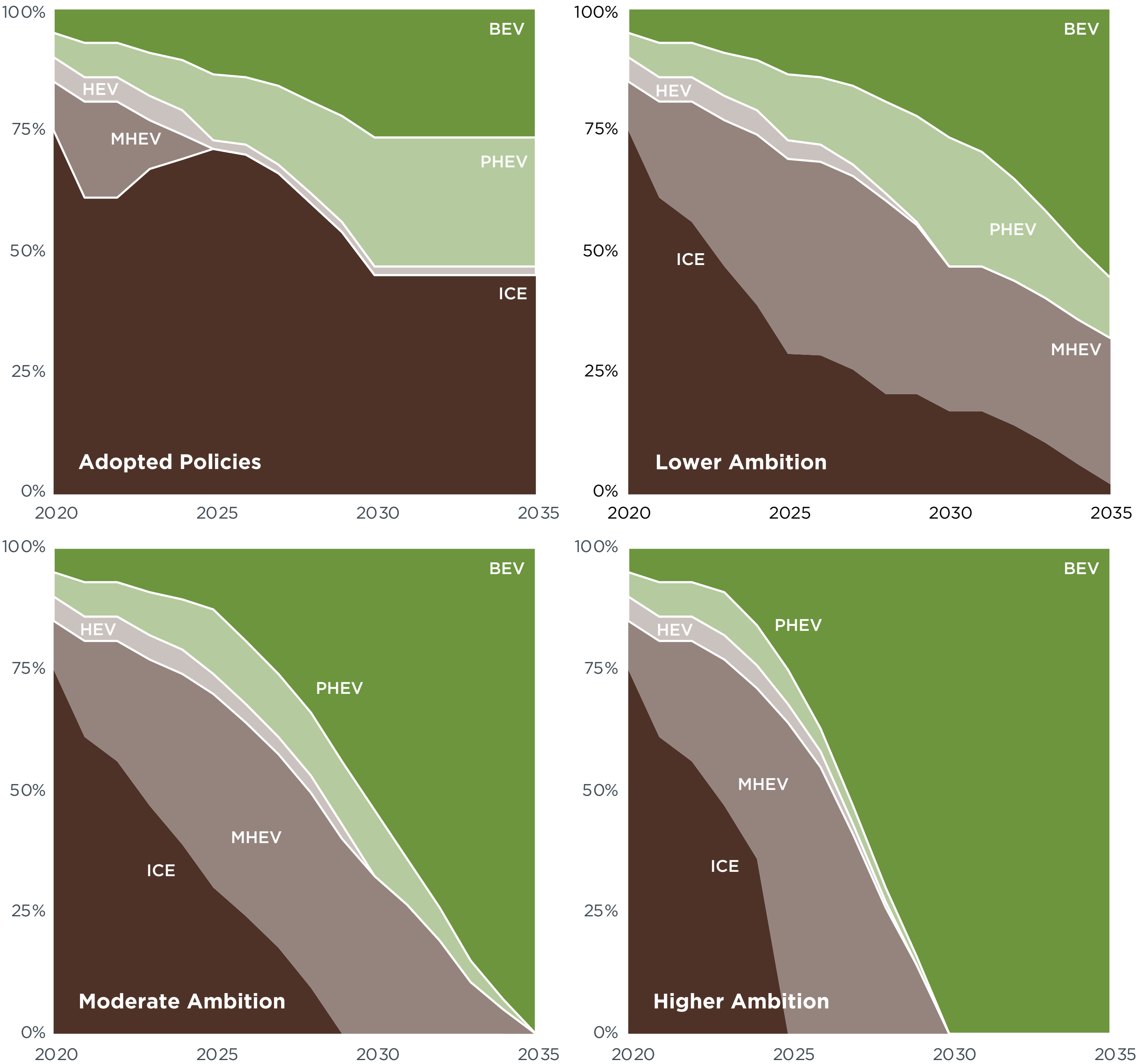

Figure 2. New registrations technology market share evolution for the four main policy scenarios.

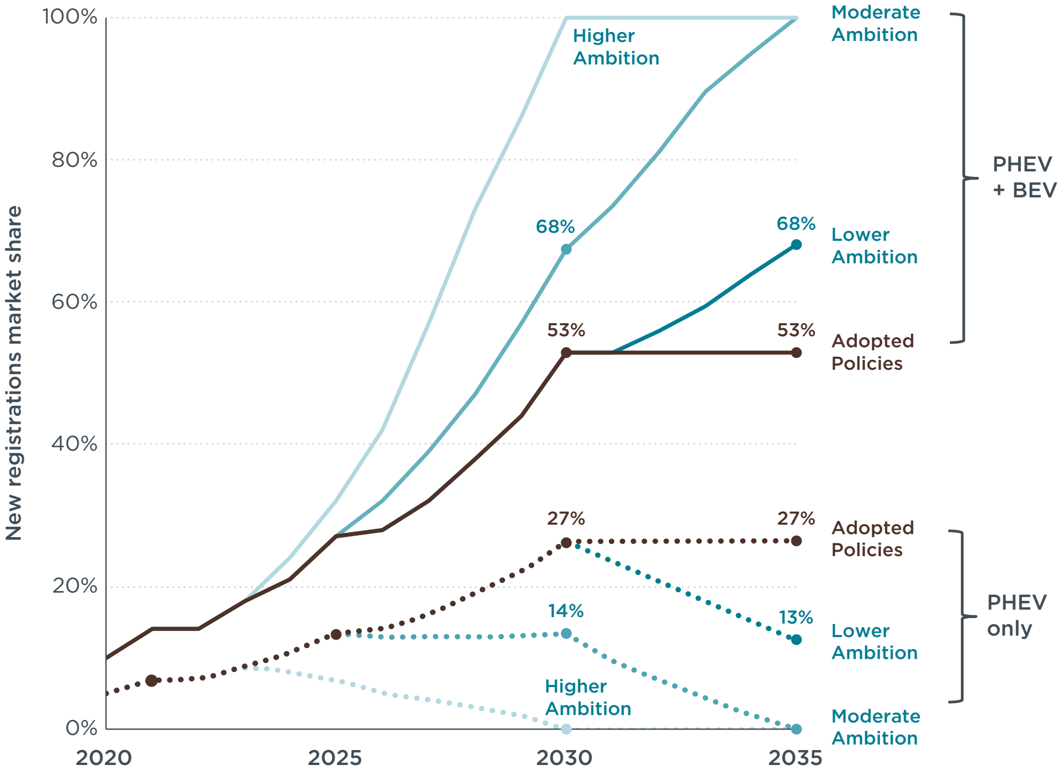

Figure 3. BEV and PHEV market share evolution for the four main policy scenarios.

Figure 4 illustrates how the average new passenger car fleet WLTP CO_2 emission level evolves in the four scenarios. In the Adopted Policies scenario, emissions decrease by 15% by 2025 and 37.5% by 2030. In the absence of a strengthened regulation, no further improvement occurs beyond 2030. In the Lower Ambition scenario, emissions decrease by 20% by 2025, 50% by 2030, and 70% by 2035. In the Moderate Ambition scenario, reductions reach 30% by 2025, 70% by 2030, and 100% by 2035. In the Higher Ambition scenario, emissions decline by 40% by 2025, the new car fleet releases zero tailpipe emissions by 2030.

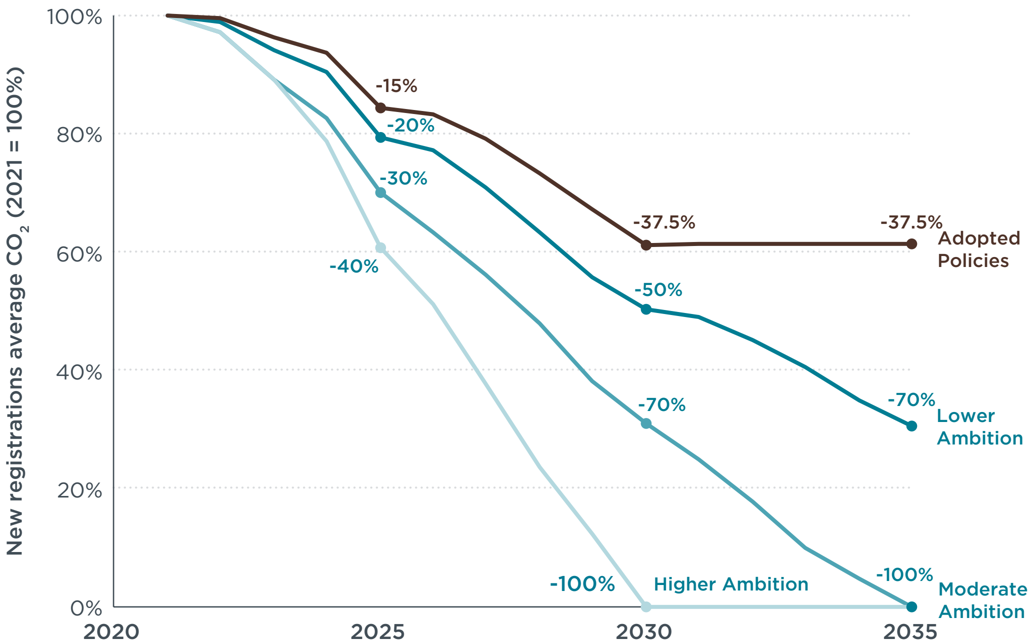

Figure 4. Average new car fleet CO_2 emission levels, including ZLEV credit adjustment, for the four main policy scenarios.

Figure 5 presents the associated direct manufacturing costs for the four main policy scenarios. Generally, costs peak around the year 2030, after which the effect of a significant decrease in BEV cost reduces the average additional direct manufacturing costs, especially in the Higher Ambition scenario.

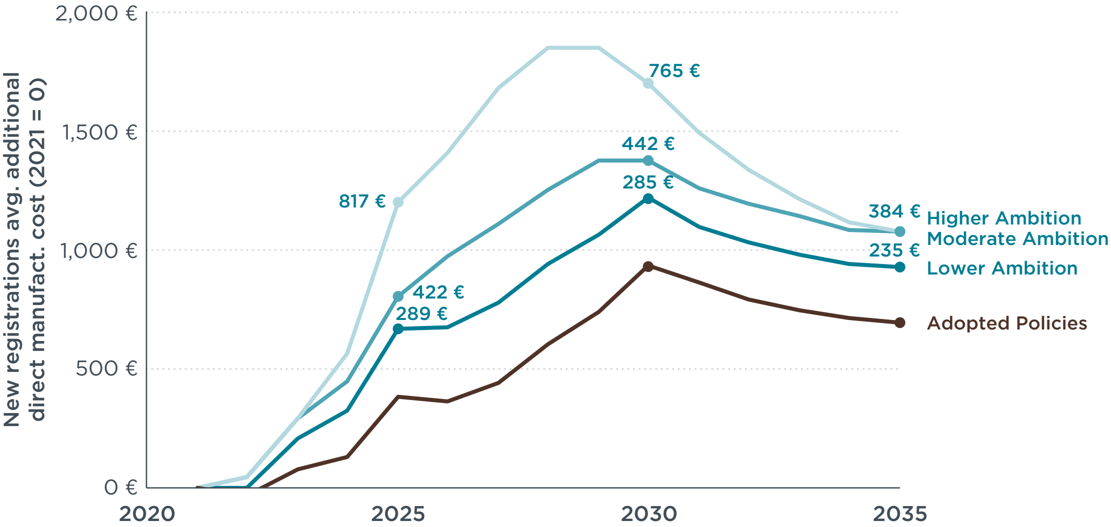

Figure 5. Additional direct manufacturing cost with a 2021 baseline. Label values refer to the cost difference vs. the Adopted Policies scenario.

Figure 6 provides the same cost data expressed in terms of the reduction of the WLTP CO_2 values of the new car fleet relative to 2021 emissions. As shown, while technology costs are higher in the Lower, Moderate, and Higher Ambition scenarios compared to the Adopted Policies scenario, the reductions of the WLTP CO_2 emission levels are also higher.

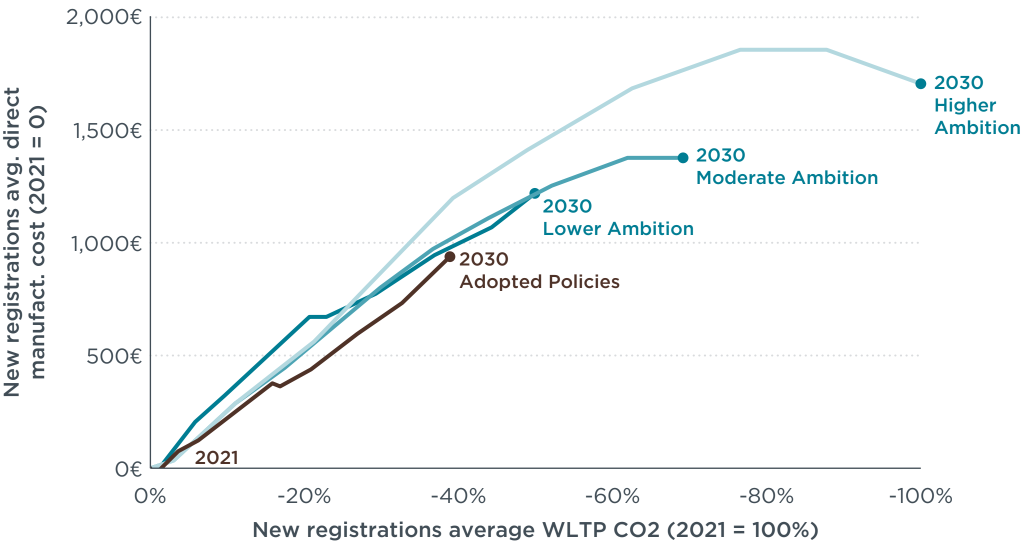

Figure 6. Additional direct manufacturing cost vs. a 2021 baseline, plotted over the WLTP CO_2 reduction vs. 2021.

COST-BENEFIT CALCULATIONS: MAIN POLICY SCENARIOS

For a cost-benefit calculation, we take as a starting point the average retail price increase per vehicle, expressed relative to a 2021 baseline. In comparison to direct manufacturing costs, retail costs also include indirect cost elements, such as research and development and warranty costs, as well as a sales tax of 20%, in line with the approximate EU-wide average (European Commission, 2020b). From these additional technology costs we deduct annual fuel cost savings compared to average new cars registered in 2021. To calculate those fuel cost savings, we convert WLTP CO_2 figures provided in Table 4 into real-world driving fuel consumption estimates, using a conversion factor of 1.14 based on Dornoff et al. (2020). The same factor is applied to estimate real-world driving electricity consumption values for BEVs and FCVs. For PHEVs, we draw on user-reported fuel consumption data from spritmonitor.de[7] and data from the ADAC EcoTest[8] to derive real-world driving fuel and electricity consumption values.[9] For the annual mileage, we assume a value of 15,000 km per year for new passenger cars.[10] With increasing vehicle age, the annual mileage decreases so that the assumed lifetime mileage is about 230,000 km. We assume the average price of gasoline, including taxes, will remain at today's level of €1.40/L for all years.[11] For electricity, a price equal to today's average EU price for household electricity, including taxes, of €0.21/kWh is assumed.[12] We discount future fuel cost savings by an annual factor of 7%, the central case from an earlier ICCT study (Meszler et al., 2018). Differences in insurance and maintenance costs for various vehicle technologies are not explicitly considered because they are minor relative to technology costs and fuel savings. Similarly, infrastructure costs are not taken into account.

Table 11 summarizes the resulting savings from a consumer perspective, compared to an average 2021 car, for the main policy scenarios in 2025, 2030, and 2035. For 2025, initial technology investments are offset within four years of ownership in the Moderate Ambition scenario and within six years in the Higher Ambition scenario. In the Adopted Policies and Lower Ambition scenarios, the payback period is more than eight years due to the depreciation of future fuel cost savings. For 2030, payback is reached within five years of ownership in the Adopted Policies scenario; within four years in the Lower Ambition scenario; within three years in the Moderate Ambition scenario; and within two years in the Higher Ambition scenario. For 2035, the payback period is three years in the Adopted Policies scenario and less than one year in all other scenarios. Focusing on 2030, the net consumer savings over an eight-year ownership period are about €300 for the Adopted Policies scenario but as high as €3,100 for the Higher Ambition scenario.

7 http://www.spritmonitor.de

8 https://www.adac.de/rund-ums-fahrzeug/tests/ecotest/

9 For PHEVs, a BMW 225xe with a WLTP electric range of 53 km—close to the PHEV-50km assumed for this analysis—spritmonitor.de reports an average real-world fuel consumption of 4.1 L/100 km. Compared to the WLTP value of 1.7 L/100km, this is factor of 2.4. For the same vehicle, ADAC EcoTest reports a fuel consumption of 7.6 L/100 km in the charge-sustaining mode, and 2.5 L/100 km (plus 17.6 kWh/100 km of energy consumption) in the mixed charge-depleting mode. Using those values, a real-world UF of 0.69 is estimated (4.1/100km = 0.31 • 7.6 L/100 km + 0.69 • 2.5 L/100 km). In a next step, the real-world electricity consumption is estimated at 12.1 kWh/100 km (0.69 • 17.6 kWh/km). For the PHEV-75 km and PHEV-100 km vehicles, the same calculations are carried out but apply real-world UFs of 0.77 and 0.85, based on estimates derived from Plötz et al., 2020. The resulting real-world fuel consumption values are 3.7 L/100 km and 3.3 L/100 km. Real-world electricity consumption values are estimated at 0.14 kWh/km and 0.15 kWh/km. All real-world values for future years are assumed to develop in parallel to the WLTP values.

10 We derive this calculation for new cars from an average annual mileage of 12,000 km for all passenger cars in the EU (Enerdata, 2021) and using an average age of 10.5 years for all passenger cars in the EU (European Automobile Manufacturers' Association, 2020).

11 For an overview on current gasoline prices across the European Union, see (European Commission, 2021b).

12 For an overview on current household electricity prices across the European Union, see (European Commission, 2021c).

Table 11. Cumulative fuel cost savings from a consumer perspective vs. an average 2021 car baseline.

Year of ownership				
2025	**Adopted Policies (-15%)**	**Lower Ambition (-20%)**	**Moderate Ambition (-30%)**	**Higher Ambition (-40%)**
1	-301 €	-730 €	-725 €	-1,277 €
2	-260 €	-637 €	-480 €	-963 €
3	-224 €	-552 €	-256 €	-676 €
4	-190 €	-475 €	**-50 €**	-413 €
5	-159 €	-404 €	137 €	-173 €
6	-131 €	-340 €	307 €	**45 €**
7	-106 €	-281 €	461 €	242 €
8	-83 €	-229 €	600 €	420 €
2030	**Adopted Policies (-37.5%)**	**Lower Ambition (-50%)**	**Moderate Ambition (-70%)**	**Higher Ambition (-100%)**
1	-661 €	-927 €	-609 €	-260 €
2	-478 €	-587 €	-148 €	**362 €**
3	-310 €	-275 €	**276 €**	933 €
4	-156 €	**10 €**	663 €	1,454 €
5	-16 €	270 €	1,016 €	1,930 €
6	**111 €**	506 €	1,337 €	2,363 €
7	227 €	720 €	1,627 €	2,754 €
8	331 €	913 €	1,889 €	3,107 €
2035	**Adopted Policies (-37.5%)**	**Lower Ambition (-70%)**	**Moderate Ambition (-100%)**	**Higher Ambition (-100%)**
1	-240 €	**143 €**	**819 €**	**819 €**
2	-52 €	570 €	1,452 €	1,452 €
3	**121 €**	963 €	2,034 €	2,034 €
4	278 €	1,321 €	2,566 €	2,566 €
5	422 €	1,648 €	3,051 €	3,051 €
6	553 €	1,945 €	3,491 €	3,491 €
7	671 €	2,214 €	3,890 €	3,890 €
8	778 €	2,457 €	4,250 €	4,250 €

Cost-benefit calculations from a societal perspective are carried out in a similar way and with the same assumptions, except that we exclude the sales, fuel, and energy taxes and set the annual discount rate at 4%, following the EU's recommended social discount rate for regulatory impact assessments (Meszler et al., 2018). We assume taxes to be 60% of the total price of gasoline[13] and 45% of the total price of electricity.[14] To account for the avoided external cost of GHG emissions, we apply a carbon price of €180 per ton of CO_2 equivalent (Umweltbundesamt, 2019). The avoided GHG emissions are based on a life-cycle assessment and include upstream emissions of fuel and electricity production, as well as battery and vehicle production, in line with a forthcoming ICCT study.[15]

13 Since 1980, the "real" price (including taxes) of transport fuel was €1.15 on average. The price without taxes was on average €0.45, see (European Environmental Agency, 2021).

14 For an overview on EU electricity tax rates, see (European Commission, 2021d).

15 G. Bieker, A global comparison of life-cycle greenhouse gas emissions of combustion engine and electric passenger cars, (forthcoming, summer 2021). For the electricity mix in particular, the average life-cycle carbon intensity during an 18-year lifetime of the vehicles is considered. It drops from 200 g CO_2 equivalent per kWh for cars driving in 2021–2038 to 104 kWh/km for 2035–2052.

Table 12 summarizes the resulting societal cost-benefit calculations. Societal savings over the lifetime of a vehicle are highest in the Moderate and Higher Ambition scenarios in 2030 and 2035. In 2025, the cumulative savings from a societal perspective already exceed the necessary technology investments in the Moderate and Higher Ambition scenarios. In comparison, the societal savings are significantly lower or even negative in the Adopted Policies and Lower Ambition scenarios.

Table 12. Summary of cost-benefit calculations for all main scenarios from a manufacturer, consumer, and societal perspective, compared to a 2021 baseline.

Scenario	Average new car CO_2 level	Additional manufacturing costs	Consumer payback period	Net consumer savings years 0-8	Societal savings vehicle lifetime
2025					
Adopted Policies	-15%	382 €	>8	-83 €	-995 €
Lower Ambition	-20%	671 €	>8	-229 €	-17 €
Moderate Ambition	-30%	804 €	4	600 €	580 €
Higher Ambition	-40%	1,199 €	6	420 €	987 €
2030					
Adopted Policies	-37.5%	938 €	6	331 €	139 €
Lower Ambition	-50%	1,223 €	4	913 €	1,752 €
Moderate Ambition	-70%	1,380 €	3	1,889 €	3,422 €
Higher Ambition	-100%	1,703 €	2	3,107 €	5,660 €
2035					
Adopted Policies	-37.5%	695 €	3	778 €	416 €
Lower Ambition	-70%	930 €	1	2,457 €	3,977 €
Moderate Ambition	-100%	1,079 €	1	4,250 €	6,856 €
Higher Ambition	-100%	1,079 €	1	4,250 €	6,856 €

SENSITIVITY SCENARIOS

To test the influence of some key assumptions, we developed two sensitivity scenarios and one variation in battery cost assumptions.

MODERATE AMBITION (PHEV & EFUEL)

The Moderate Ambition (PHEV & eFuel) scenario is identical to the Moderate Ambition scenario for the years 2021–2025. Beyond 2025, however, we assume that manufacturers will heavily rely on PHEVs, in combination with a hypothetical eFuel crediting mechanism in the CO_2 standards, to meet the defined fleet target of 70% lower WLTP CO_2 emission values by 2030 and zero tailpipe CO_2 emissions by 2035. By 2030, the share of PHEVs increases to 50%, while BEVs account for 25% of the market. The remainder of vehicles are MHEVs. In 2035, PHEVs account for 75% of the market while BEVs remain at 25%. With the available potential of eFuel, it is possible to compensate for part of the increase in WLTP CO_2 emission levels from the increased PHEV share, but it is not possible to reach full decarbonization: CO_2 is reduced only by about 90% relative to a 2021 baseline due to the limited availability of eFuels assumed for the analysis (Table 13).

Table 13. Summary of key characteristics of the Moderate Ambition (PHEV & eFuel) scenario.

	2021	2025	2030	2035
BEV share	7%	13.5%	25%	25%
BEV-350km	*7%*	*10%*	*10%*	*10%*
BEV-450km	*0%*	*2%*	*10%*	*10%*
BEV-550km	*0%*	*1%*	*5%*	*5%*
CO_2 (WLTP)	0 g/km	0 g/km	0 g/km	0 g/km
PHEV share	7%	13.5%	50%	75%
CO_2 (WLTP)	43 g/km	31 g/km	23 g/km	20 g/km
average progress (WLTP)	n/a	-8.0% p.a.	-6.1% p.a.	-3.0% p.a.
ZLEV share	14%	27%	75%	100%
unweighted / weighted	10%	21%	60%	80%
HEV share	5%	4%	0%	0%
MHEV share	20%	40%	25%	0%
Conventional ICE share	61%	29%	0%	0%
Total ICE share	86%	73%	25%	0%
CO_2 (WLTP)	130 g/km	109 g/km	103 g/km	n/a
average annual progress	n/a	-4.3% p.a.	-1.0% p.a.	n/a
New car CO_2 (WLTP)	115 g/km	80 g/km	35 g/km	12 g/km
excl. ZLEV credit	*n/a*	*84 g/km*	*37 g/km*	*n/a*
vs. 2021	n/a	**-30%**	**-70%**	**-90%**

MODERATE AMBITION (FUEL CELL)

The Moderate Ambition (Fuel Cell) scenario is identical to the Moderate Ambition scenario for all years until 2030. Beyond 2030, we assume that manufacturers will deploy an increasing share of FCVs so that a full phase-out of combustion engine vehicles is reached by 2035, when the market consists of 40% FCVs and 60% BEVs (Table 14).

Table 14. Summary of key characteristics of the Moderate Ambition (Fuel Cell) scenario.

	2021	2025	2030	2035
FCV share	0%	0%	0%	40%
BEV share	7%	13.5%	54%	60%
BEV-350km	*7%*	*10%*	*28%*	*28%*
BEV-450km	*0%*	*2%*	*16%*	*16%*
BEV-550km	*0%*	*1%*	*10%*	*16%*
CO_2 (WLTP)	0 g/km	0 g/km	0 g/km	0 g/km
PHEV share	7%	13.5%	13.5%	0%
CO_2 (WLTP)	43 g/km	31 g/km	23 g/km	n/a
average progress (WLTP)	n/a	-8.0% p.a.	-6.1% p.a.	n/a
ZLEV share	14%	27%	68%	100%
unweighted / weighted	10%	21%	63%	100%
HEV share	5%	4%	0%	0%
MHEV share	20%	40%	32.5%	0%
Conventional ICE share	61%	29%	0%	0%
Total ICE share	86%	73%	32.5%	0%
CO_2 (WLTP)	130 g/km	109 g/km	103 g/km	n/a
average annual progress	n/a	-4.3% p.a.	-1.0% p.a.	n/a
New car CO_2 (WLTP)	115 g/km	80 g/km	35 g/km	0 g/km
excl. ZLEV credit	*n/a*	*84 g/km*	*37 g/km*	*n/a*
vs. 2021	n/a	**-30%**	**-70%**	**-100%**

Figure 7 and Figure 8 summarize the technology market share assumptions for the two sensitivity scenarios. In comparison to the Moderate Ambition scenario, the Moderate Ambition (PHEV & eFuels) scenario relies on a much stronger uptake of PHEVs beyond 2030, at the expense of BEVs. In the Moderate Ambition (Fuel Cell) scenario, FCVs capture 40% of the market by 2035, again at the expense of BEVs.

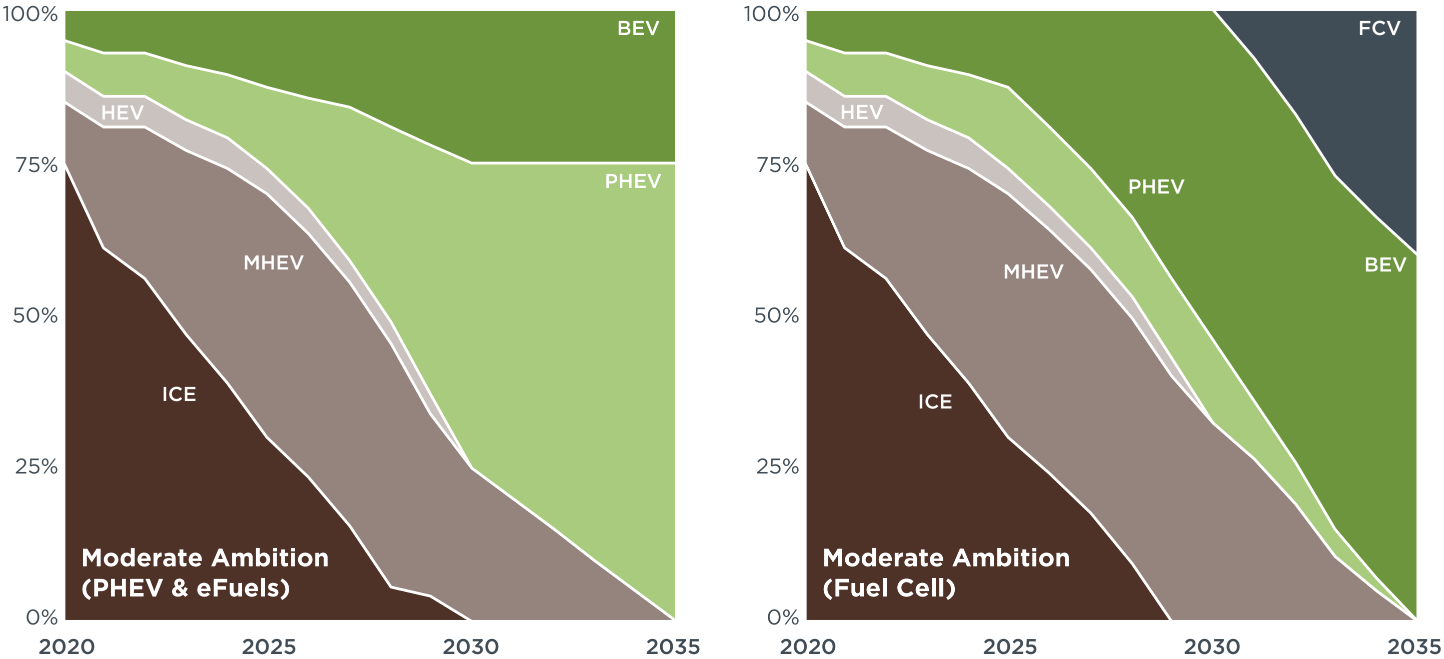

Figure 7. Technology market share evolution for the two sensitivity scenarios.

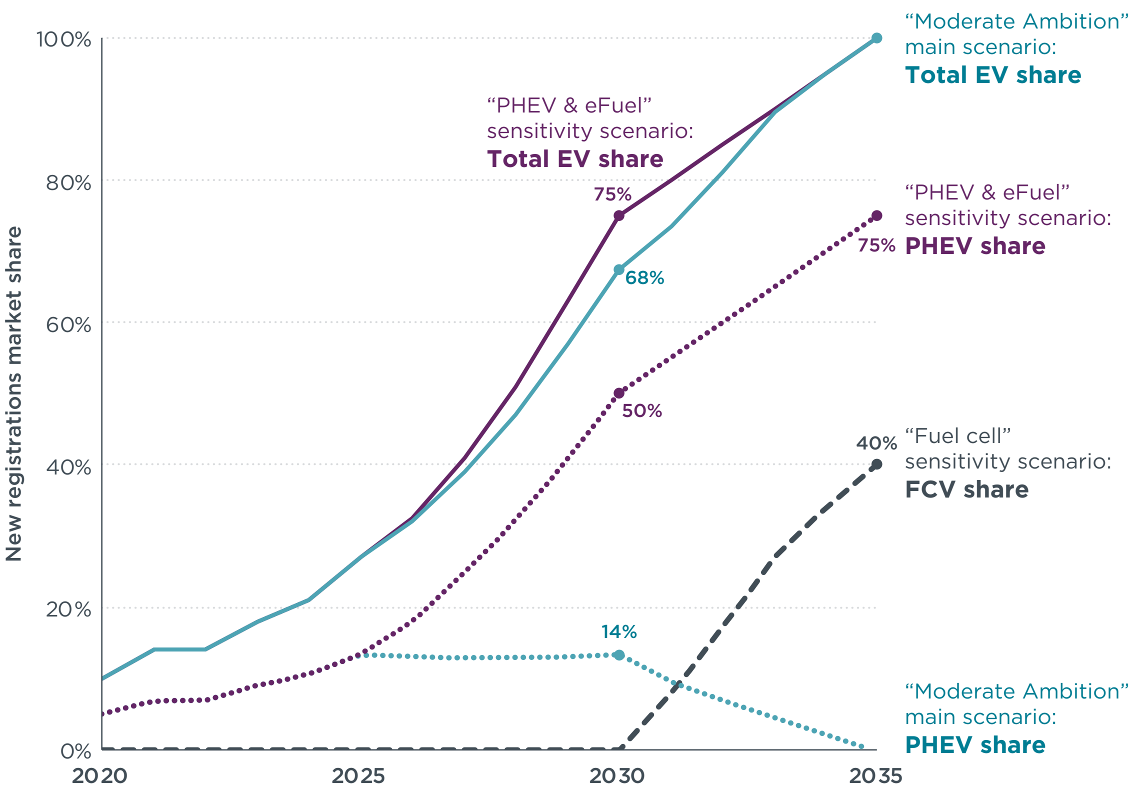

Figure 8. BEV and PHEV market share evolution for the two sensitivity scenarios.

Figure 9 presents the resulting required technology cost investments for the two sensitivity scenarios, relative to a 2021 baseline. For comparison, the figure also shows these required investments for the regular Moderate Ambition and Adopted Policies scenarios. The direct manufacturing costs in the Moderate Ambition (PHEV & eFuel) scenario in 2030 are about 60% higher than in the Moderate Ambition scenario: In 2035, the sensitivity scenario is more than twice as expensive as the main scenario. Relative to the Adopted Policies scenario, the required technology investments reach €1,300 by 2030 and €2,150 by 2035. For the Moderate Ambition (Fuel Cell) scenario, the additional cost is more modest: €760 by 2035 relative to the Adopted Policies scenario.

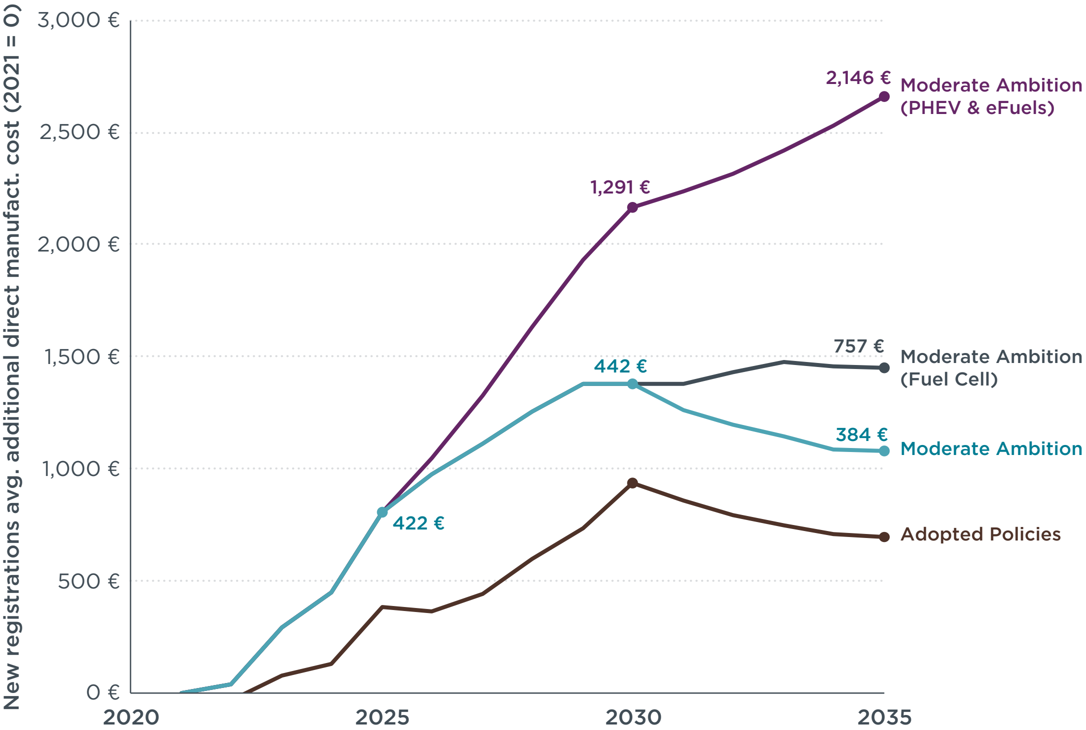

Figure 9. Additional direct manufacturing cost with a 2021 baseline. Label values refer to the cost difference compared to the Adopted Policies scenario.

Figure 10 illustrates how the same CO_2 reduction (70%) is achievable by 2030 at a much smaller increase in direct manufacturing costs in the Moderate Ambition scenario, compared to the Moderate Ambition (PHEV & eFuel) sensitivity scenario.

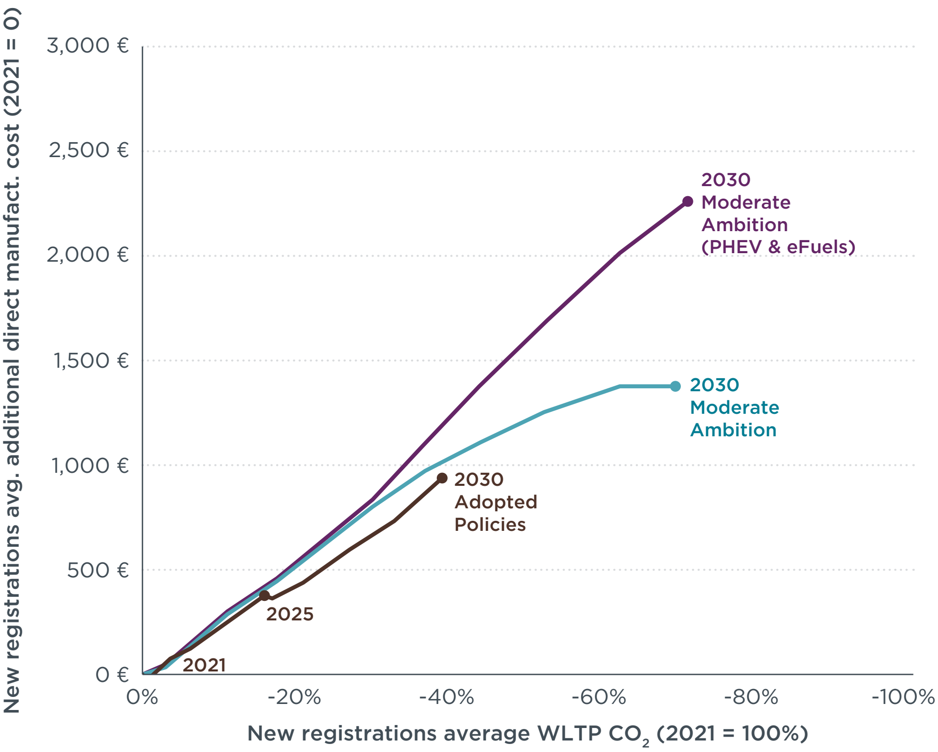

Figure 10. Additional direct manufacturing costs with a 2021 baseline, plotted over the CO_2 reduction compared to 2021.

COST-BENEFIT CALCULATIONS: SENSITIVITY SCENARIOS

To calculate the sensitivity scenarios, we apply the same approach and assumptions as for the main scenarios. For the Moderate Ambition (Fuel Cell) scenario, we assume the price for hydrogen for the consumer in 2030 and 2035 to be at €6.50 per kg for a 50:50 mix of "blue" hydrogen (produced from fossil natural gas, in combination with carbon capture and storage) and "green" hydrogen (produced from renewable sources) (Hydrogen Council, 2020). For the societal calculations, we assume the tax share of the hydrogen price in 2030 and 2035 to be identical to electricity, at 45%. The upstream emissions from producing a 50:50 mix of blue and green hydrogen are assumed to be 2,360 g CO_2 equivalent/kg, based on an upcoming ICCT report.

Table 15 summarizes the resulting savings from a consumer perspective. For the Moderate Ambition (PHEV & eFuel) scenario, it is impossible within the first eight years of ownership to make up for the necessary technology and fuel investments in either 2030 or 2035. The Moderate Ambition (Fuel Cell) scenario is identical to the main scenario for 2030. For 2035, payback is reached within the second year of ownership in the fuel cell scenario but with fewer savings for consumers than in the main scenario.

Table 15. Cumulative savings from a consumer perspective with a 2021 baseline.

2030	Year of ownership	Moderate Ambition (-70%)	MA (PHEV & eFuel) (-70%)	MA (Fuel Cell) (-70%)
	1	-609 €	-2,472 €	*identical to Moderate Ambition main scenario*
	2	-148 €	-2,083 €	
	3	**276 €**	-1,725 €	
	4	663 €	-1,399 €	
	5	1,016 €	-1,101 €	
	6	1,337 €	-830 €	
	7	1,627 €	-585 €	
	8	1,889 €	-364 €	

2035	Year of ownership	Moderate Ambition (-100%)	MA (PHEV & eFuel) (-90%)	MA (Fuel Cell) (-100%)
	1	**819 €**	-3,296 €	14 €
	2	1,452 €	-2,887 €	**485 €**
	3	2,034 €	-2,511 €	916 €
	4	2,566 €	-2,167 €	1,311 €
	5	3,051 €	-1,854 €	1,670 €
	6	3,491 €	-1,569 €	1,997 €
	7	3,890 €	-1,311 €	2,293 €
	8	4,250 €	-1,079 €	2,560 €

Table 16 provides a summary of the resulting cost-benefit calculations. Societal savings over the lifetime of a vehicle are drastically lower in the PHEV & eFuel scenario, compared to the main scenario. Savings in the Fuel Cell sensitivity scenario are about 25% lower than in the main scenario.

Table 16. Summary of cost-benefit calculations for the Moderate Ambition policy scenarios from a manufacturer, consumer, and societal perspective, compared to a 2021 baseline.

Scenario	Average new car CO_2 level	Additional manufacturing costs	Consumer payback period	Net consumer savings years 0-8	Societal savings vehicle lifetime
			2030		
Moderate Ambition	-70%	1,380 €	3	1,889 €	3,422 €
MA (PHEV & eFuel)	-70%	2,163 €	>8	-364 €	1,142 €
MA (Fuel Cell)	*identical to Moderate Ambition main scenario*				
			2035		
Moderate Ambition	-100%	1,079 €	1	4,250 €	6,856 €
MA (PHEV & eFuel)	-90%	2,663 €	>8	-1,079 €	-1,073 €
MA (Fuel Cell)	-100%	1,452 €	2	2,560 €	5,170 €

VARIATION IN BATTERY COST ASSUMPTIONS

For all scenarios in this analysis, we apply an annual decrease in vehicle battery costs of 7%, in line with the central case in an earlier ICCT study (Lutsey & Nicholas, 2019). To illustrate the influence of battery price assumptions, we also run a lower-case variation with an annual reduction rate of 9% and an upper-case variation with an annual reduction rate of 5%. Table 17 summarizes the resulting battery cost assumptions. While the central and lower-case battery cost assumptions tend to follow observed market developments and industry announcements (Lutsey et al., 2021), the upper-case variation assumptions reflect significantly slower technology improvements than observed to date and are considered unlikely for the expected rate of future progress.

Table 17. Overview of battery pack cost assumptions for BEVs.

	2021	2025	2030	2035
Lower-case variation	141 €/kWh	97 €/kWh	60 €/kWh	51 €/kWh
Central case		105 €/kWh	73 €/kWh	63 €/kWh
Upper-case variation		114 €/kWh	88 €/kWh	76 €/kWh

Applying the lower-case variation battery cost estimates, the additional retail price for a BEV with 350-km range would be notably lower than in the central case, and the BEV would reach purchase price parity with a MHEV ICE approximately one year earlier, in 2028 (Figure 11). Cost parity for a BEV with a similar electric range is reached about two years earlier in the United States, according to a previous study (Lutsey & Nicholas, 2019), largely due to the higher cost of the comparably higher engine power (150 kW vs. 98 kW in the EU) baseline vehicle in the United States.

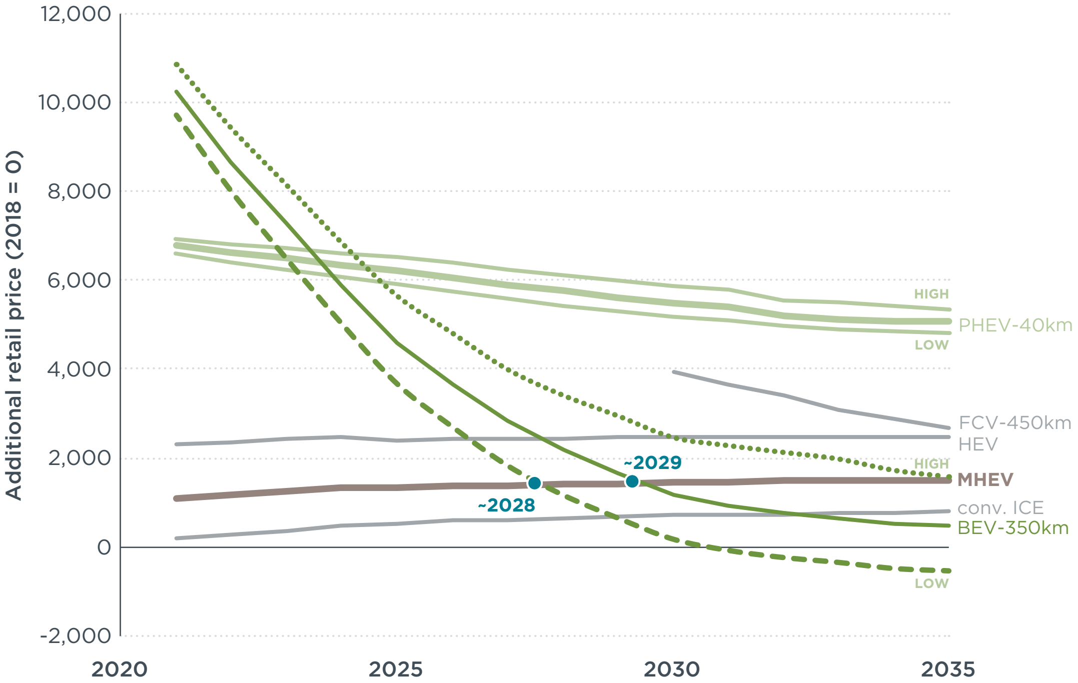

Figure 11. Assumed retail price developments for various vehicle types, relative to a 2018 baseline vehicle.

Importantly, cost parity for the consumer (i.e., total cost of ownership independent of variations in battery prices), is reached several years before purchase price parity. Figure 12 applies the same assumptions for real-world driving consumption values, mileage, and discounted future savings to illustrate the development of additional total cost of ownership for various vehicle types over time. Initially, in 2021, the purchase price of PHEVs, BEVs, and FCVs strongly surpasses the expected fuel cost savings. Without adequate subsidies (about €5,000 for a PHEV-50km and €6,900 for a BEV-350km), it would therefore be irrational for the average consumer to purchase these vehicle types. The situation changes by 2025, when the BEV-350km becomes cost-efficient for the consumer without any subsidies. By 2030, the BEV-450km and the BEV-550km are also cost-efficient and are much more attractive to consumers —from a cost perspective than ICE-based vehicles, including MHEVs and PHEVs.

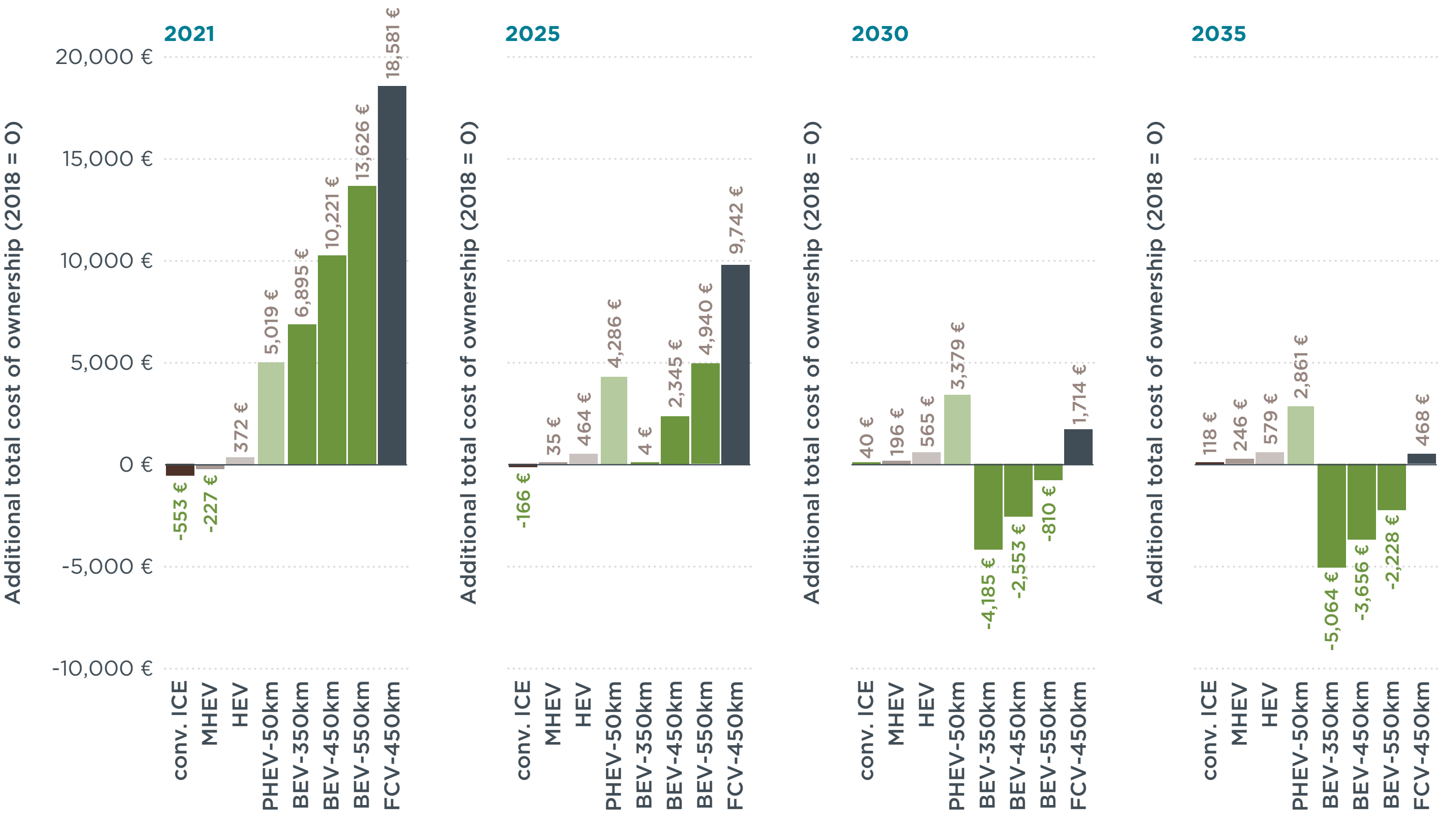

Figure 12. Additional total cost of ownership (vehicle purchase price and fuel cost savings) for the consumer, relative to a 2018 baseline vehicle.

DISCUSSION

COMPARISON WITH MANUFACTURER ANNOUNCEMENTS

All of the scenarios we assessed rely on a strong uptake of electric vehicles to meet the respective WLTP CO_2 emission target values. By 2025, the combined market share of BEVs and PHEVs reaches 32% in the Higher Ambition scenario and 27% in all other scenarios. By 2030, the share varies between 53% (Adopted Policies and Lower Ambition), 68% (Moderate Ambition), and 100% (Higher Ambition). Table 18 compares these assumed technology market shares with the shares in 2020 and with publicly announced targets, differentiated by manufacturer.

In 2020, electric vehicle market shares rose significantly for most manufacturers (e.g., 21% in the case of Daimler). The average market share in 2020 was 11%, compared to 3% in 2019 (Mock et al., 2021). For 2025, Toyota intends to sell 20% of its new cars as PHEV or BEV; Daimler is targeting 25%, BMW 33%, Porsche 50%, and Renault 65%. In the case of Volvo, the company has announced a goal to sell half of its new cars by 2025 as BEVs. For 2030, Volvo (100%), Ford (100%), BMW (50%), Daimler (>50%), and VW (60%) have publicly announced their planned electric vehicle market shares.

These announcements are well in line with the assumed market shares for the Adopted Policies scenario. In response to more stringent regulatory targets, we expect that manufacturers will adapt their product plans, deploying more electric vehicles to the market than they envision under the current policy. For example, Volkswagen's Head of Group Strategy was quoted to be planning for 70% of the group's new car sales in 2030 to be BEVs (Electrive, 2021).

None of the passenger car manufacturers has currently put forward plans for a significant share of FCVs by 2030, which is in line with the assumptions for the Moderate Ambition (Fuel Cell) scenario, which only foresees a significant share of FCVs in 2035.

None of the major car manufacturers is, at this point, publicly supporting a push towards eFuels. Volkswagen calls the production of eFuels from excess renewable energy "complex [and] expensive, with limited climate impact and a low degree of efficiency," and refers to the use of renewable hydrogen for passenger cars as "nonsense" (Volkswagen, 2020). Meanwhile, some combustion engine part suppliers and parts of the oil industry advocate for the incorporation of credits for eFuels into the EU vehicle CO_2 regulation, a policy reflected in the Moderate Ambition (PHEV & eFuel) scenario.

Table 18. Overview of technology market shares by manufacturer in 2020 and publicly announced targets for future years.

	2020						
	Market	MHEV	HEV	PHEV	BEV	FCV	Announced targets for future years
VW Group (Audi, Porsche, SEAT, Škoda, VW)	25%	7%	0%	4%	7%	0%	Volkswagen: 2030: 60% BEV (Europe) Porsche: 2025: 50% EVs (incl. PHEV, Europe)
PSA-Opel (Citroën, DS, Opel, Peugeot)	15%	0%	0%	3%	4%	0%	
Renault (Dacia, Renault)	10%	0%	0%	1%	9%	0%	2025: 35% HEV and PHEV, 30% BEV (Europe) 2030: 90% (incl. PHEV, Europe)
Ford-Volvo (Ford, Volvo)	8%	20%	1%	11%	1%	0%	Ford: 2026: 100% EVs (incl. PHEV); 2030: 100% BEV (Europe) Volvo: 2025: 50% BEV; 2030: 100% BEV
FCA-Tesla-Honda (Alfa Romeo, Fiat, Honda, Jeep, Lancia, Tesla)	7%	12%	3%	1%	12%	0%	
Toyota-Mazda (Lexus, Mazda, Toyota)	7%	10%	56%	1%	1%	0%	2025: 70% HEV, 10% PHEV, 10% BEV/FCV (Europe)
BMW (BMW, Mini)	7%	9%	0%	12%	5%	0%	2021: 25%, 2025: 33%, 2030: 50% EVs (incl. PHEV, Europe)
Daimler (Mercedes, Smart)	6%	6%	0%	15%	6%	0%	2025: 25% (incl. PHEV); 2030: >50% EVs (incl. PHEV, Europe)

Note. Data are derived from Mock et al. (2021) and Der Spiegel (2021).

COMPARISON WITH EARLIER TECHNOLOGY POTENTIAL AND COST ESTIMATES

Technology potential and cost estimates are subject to continuous changes as technologies mature and more precise estimates for future developments become available. The current 2021 ICCT estimates for the additional manufacturing costs of 2030 cars stand at about the same level as a previous 2018 assessment (Table 19). For 2035, costs are about 15% lower.

ICCT estimates for 2030 are about 50% lower than the most recent assessment of the European Commission from 2017. The difference is attributable, for example, to the European Commission's higher battery cost assumptions (146 €/kWh compared to ICCT's 63 €/kWh for 2030 and the ICCT taking into account eco-innovation and test cycle flexibility credits. The European Commission is expected to will produce an updated assessment of technology potential and costs toward the middle of 2021.

Industry-based assessments tend to arrive at significantly higher cost estimates than independent assessments. Generally, in practice, costs are much lower than assessments project. For example, vehicle manufacturers announced a cost estimate of €1,000 for reaching a 130 g/km (NEDC) CO_2 target by 2015, while an initial estimate on behalf of the European Commission estimated compliance costs of €620. Later, once the target was met, an ex-ante assessment developed on behalf of the European Commission found that the actual cost increase stood only around €200.

Table 19. Estimated additional manufacturing cost for various CO_2 reduction scenarios differentiated by year and source of estimate.

130 g/km (NEDC) by 2015 (vs. 2010 baseline)	Manufacturing cost
European Commission estimate (TNO, 2006)	620 €
Industry estimate (ACEA, 2009)	1,000 €
European Commission estimate (AEA, 2015)	200 €
95 g/km (NEDC) by 2021 (vs. 2010 baseline)	
European Commission estimate (TNO, 2011)	1,200 €
Industry-based estimate (IKA, 2012)	1,990 €
ICCT estimate (ICCT, 2013)	960 €
ICCT estimate (ICCT, 2016)	460 €
-15% by 2025 (vs. 2021 baseline)	
Industry-based estimate (IKA, 2015)	1,850 €
European Commission estimate (AEA, 2015)	900 €
ICCT estimate (ICCT, 2016)	420 €
European Commission estimate (EC, 2017)	380 €
ICCT estimate (ICCT, 2021)	380 €
-37.5% by 2030 (vs. 2021 baseline)	
2017 European Commission estimate (EC, 2017)	1,610 €
2018 ICCT estimate (ICCT, 2018)	870 €
2021 ICCT estimate (ICCT, 2021)	940 €
-50% by 2030 (vs. 2021 baseline)	
2017 European Commission estimate (EC, 2017)	2,750 €
2018 ICCT estimate (ICCT, 2018)	1,160 €
2021 ICCT estimate (ICCT, 2021)	1,220 €
-70% by 2030 (vs. 2021 baseline)	
2018 ICCT estimate (ICCT, 2018)	1,640 €
2021 ICCT estimate (ICCT, 2021)	1,400 €

Note. European Commission estimates refer to medium/central cost scenarios. We interpolated values for CO_2 emissions reduction of -37.5% in 2030 based on scenarios for -30% and -40%. (See Dornoff et al. (2018), European Commission (2017), Hill et al. (2016), Institute for Automotive Engineering (2012), Mock (2015), Smokers et al. (2006), and Smokers et al. (2011).

SUMMARY AND CONCLUSIONS

For the 2021 to 2035 time period, moderate potential remains for decreasing the CO_2 emission levels of combustion engine vehicles. Based on technology data developed by industry-recognized automotive engineering services providers, this assessment indicates that a 15% reduction of the WLTP CO_2 emission value is still feasible for conventional ICEs by 2035. A full transition towards MHEVs would enable an additional reduction of approximately 15% in WLTP CO_2 emissions. However, this additional production of ICEs comes at a cost, constraining improvements in the efficiency of the engine and vehicle and limiting reductions in air pollutant emissions. As a result of these constraints in combination with future EU CO_2 emission targets, diesel passenger cars are expected to become cost-inefficient for the EU market and were therefore disregarded in this analysis. For gasoline cars, we estimate additional direct manufacturing costs will increase by €1,150 for model year 2035 vehicles that fully exploit the remaining CO_2 reduction potential of conventional ICE as well as MHEV technology.

Electric vehicles offer a much greater potential for reducing WLTP CO_2 emission levels, i.e., between about 80% in the case of a PHEV with 50-km electric range by 2035, and up to 100% in the case of BEVs and FCVs. Note that in real-world driving conditions, the tailpipe CO_2 emission of PHEVs are found to be on average 2–4 times higher. The additional manufacturing costs are initially high, estimated at around €4,900 for a BEV with 350-km electric range in 2021. But expected advances in battery technology and increasing scale of production hold significant potential for cost reductions. In the case of a lower range BEV, additional costs are estimated to decrease to about €1,350 by 2035. While PHEVs currently have a cheaper additional direct manufacturing cost (about €4,900 in 2021 for a 50-km electric range vehicle), we estimate the potential cost reduction for PHEVs to be much smaller, declining to about €3,700 by 2035.

The scenarios investigated in this paper assess the potential reduction in WLTP CO_2 emissions levels and associated estimated manufacturing costs for various policy pathways:

» In the Adopted Policies scenario, manufacturers comply with the currently implemented targets of a reduction of the 2021 average WLTP CO_2 emission level of -15% by 2025 and -37.5% by 2030 but make no efforts to exceed the necessary levels of CO_2 reduction and electric vehicle deployment. The remaining potential of ICEs is untouched, and electric vehicle market shares stagnate from 2030 onwards.

» The Lower Ambition scenario assumes that current targets are strengthened to -20% by 2025, -50% by 2030, and -70% for 2035. It thereby ensures that manufacturers tap some of the remaining ICE potential (reducing WLTP CO_2 emission levels by about 1% p.a.) and further increase the market share of electric vehicles, so that BEVs account for about half of new car sales by 2035.

» For the Moderate Ambition scenario, the CO_2 targets are increased to -30% by 2025, -70% by 2030, and -100% by 2035. To comply, vehicle manufacturers must exploit most of the remaining potential of ICEs at a rate of about 4% CO_2 reduction p.a. in WLTP between 2021 and 2025, including improvements in road load and transitioning to MHEVs. In addition, PHEVs are phased out and replaced by more cost-efficient BEVs faster than in the Lower Ambition scenario. BEVs reach a market penetration of about 50% by 2030 and 100% by 2035.

» In the Higher Ambition scenario, zero tailpipe CO_2 emissions of the new car fleet are achieved by 2030 due to a rapid transition toward BEVs and full exploitation of with remaining ICE potential in the transition years.

For all scenarios, direct manufacturing costs increase compared to the 2021 baseline, between about €400 in the Adopted Policies scenario in 2025 to about €1,700 in the

Higher Ambition scenario in 2030 (Table 20). For 2035, costs decline compared to 2030, mainly due to improved learning for electric vehicle technologies.

Table 20. Summary of cost-benefit calculations for all main scenarios from a manufacturer, consumer, and societal perspective, compared to a 2021 baseline.

Scenario	Average new car CO_2 level	Additional manufacturing costs	Consumer payback period	Net consumer savings years 0-8	Societal savings vehicle lifetime
2025					
Adopted Policies	-15%	382 €	>8	-83 €	-995 €
Lower Ambition	-20%	671 €	>8	-229 €	-17 €
Moderate Ambition	-30%	804 €	4	600 €	580 €
Higher Ambition	-40%	1,199 €	6	420 €	987 €
2030					
Adopted Policies	-37.5%	938 €	6	331 €	139 €
Lower Ambition	-50%	1,223 €	4	913 €	1,752 €
Moderate Ambition	-70%	1,380 €	3	1,889 €	3,422 €
Higher Ambition	-100%	1,703 €	2	3,107 €	5,660 €
2035					
Adopted Policies	-37.5%	695 €	3	778 €	416 €
Lower Ambition	-70%	930 €	1	2,457 €	3,977 €
Moderate Ambition	-100%	1,079 €	1	4,250 €	6,856 €
Higher Ambition	-100%	1,079 €	1	4,250 €	6,856 €

It is important to recognize the savings that each of the scenarios will produce for consumers, mainly due to reduced fuel cost, and society overall, mainly due to reduced energy cost as well as avoided CO_2 emissions. From a consumer perspective, for 2025, the Moderate Ambition scenario provides the most favorable payback period: Initial technology investments are fully paid for within four years of ownership. For 2030, the Higher and Moderate Ambition scenarios ensure the quickest payback period of two to three years. For 2035, technology investments pay back within one to two years for all scenarios except the Adopted Policies scenario. All scenarios apply the conservative assumption that manufacturers would pass on all additional costs to consumers and not absorb part of the cost increase by making cost reductions in other areas, as has been the case in the past. From a societal perspective, in all years those scenarios with the highest CO_2 reduction are also the scenarios that provide the greatest savings. In other words, the higher the CO_2 savings, the higher the benefits for society.

Two sensitivity scenarios illustrate the potential role of eFuel and FCVs. The Moderate Ambition (PHEV & eFuel) scenario assumes manufacturers meet the Moderate Ambition CO_2 targets by heavily relying on PHEVs and eFuel instead of BEVs. As a result, direct manufacturing costs increase by more than 60% by 2030 and are more than twice as high as those of the Moderate Ambition scenario by 2035 (Table 21). Savings for consumers and society are lost, turning instead into high costs, without an opportunity to pay back technology and fuel investments within the typical holding period or lifetime of a vehicle. The Moderate Ambition (Fuel Cell) scenario assumes that from 2030 onwards, FCVs will reach a market share of 40% by 2035. We estimate manufacturing costs to increase only slightly compared to the Moderate Ambition scenario. Consumer savings are lower, though payback is still reached within the second year of ownership. From a societal perspective, savings are about 25% lower than in the main Moderate Ambition scenario.

Table 21. Summary of cost-benefit calculations for the Moderate Ambition policy scenarios from a manufacturer, consumer and societal perspective, compared to a 2021 baseline.

Scenario	Average new car CO_2 level	Additional manufacturing costs	Consumer payback period	Net consumer savings years 0-8	Societal savings vehicle lifetime
2030					
Moderate Ambition	-70%	1,380 €	3	1,889 €	3,422 €
MA (PHEV & eFuel)	-70%	2,163 €	>8	-364 €	1,142 €
MA (Fuel Cell)	*identical to Moderate Ambition main scenario*				
2035					
Moderate Ambition	-100%	1,079 €	1	4,250 €	6,856 €
MA (PHEV & eFuel)	-90%	2,663 €	>8	-1,079 €	-1,073 €
MA (Fuel Cell)	-100%	1,452 €	2	2,560 €	5,170 €

The technology market shares assumed for the Adopted Policies scenario align with the current performance of manufacturers and the electric vehicle deployment rates that some manufacturers have publicly announced for future years. With strengthened CO_2 targets, it is expected that manufacturers will adapt their product plans to deploy more advanced vehicle technologies than they do today. Especially for electric vehicles, where advances in battery technology have occurred quickly in recent years, the assumed cost reductions in the main scenarios are conservative. In the future, further developments in battery chemistry could allow for a larger decrease in cost than this analysis projects. Even with these conservative battery cost estimates, we project vehicle price parity for BEVs toward the late 2020s, with parity in total cost of ownership for the consumer occurring by about 2025.

The following conclusions can be drawn from the analysis:

» In order to meet its agreed climate protection targets, the European Union must revise its sector-specific CO_2 reduction targets, including those for passenger cars. The Lower Ambition scenario would bring CO_2 levels closer to existing targets, with 2,040 Mt cumulative CO_2 savings between 2021 and 2030 but would still miss full decarbonization by 2050. The Moderate Ambition scenario (-2,970 Mt CO_2), and the Higher Ambition scenario especially (-3,520 Mt CO_2), would be more favorable from a climate protection perspective (Buysse et al., 2021).

» All scenarios require larger investments in advanced vehicle technologies, with the highest costs reached in model year 2030. Taking into account fuel and CO_2 emission savings, the Moderate and Higher Ambition scenarios provide the most favorable consumer payback period (two to three years) and societal lifetime savings (about €3,400 to €6,100) in 2030. For 2035, all three advanced scenarios offer a favorable cost-benefit ratio both for the consumer and society, with the Higher Ambition scenario providing the highest savings for society. For 2025, the Moderate Ambition scenario offers the lowest consumer payback period of four years, combined with a reasonable outlook from a society perspective. In summary, the Higher Ambition scenario provides the most benefits throughout the years 2025–2035.

» Relying on PHEVs in combination with eFuel misses the 2035 CO_2 reduction target of the Moderate Ambition scenario and results in extraordinarily high cost. Introducing any crediting mechanism for eFuel into the new vehicle CO_2 regulation might also be unduly extended to similar credits for biofuels, with much lower cost but significantly worse environmental and climate impacts than eFuel.

» Fuel cell vehicles may provide a viable option for the passenger car segment, at least for 2030 and beyond. However, even optimistically assuming a high share of renewable hydrogen and following optimistic cost estimates from the hydrogen industry, the resulting cost benefit calculations are about 25% less favorable from societal perspective than if relying on a stronger uptake of BEVs. Against this background, it is questionable whether vehicle manufacturers would be willing to develop another production and distribution chain in parallel to that for BEVs.

» If manufacturers strive toward exploiting the benefits of the current ZLEV credits (i.e., a 5% relaxation of their respective fleet targets), this will result in neglecting most of the available remaining technology potential of ICEs. In order to tap all available potential, the 2025 and 2030 fleet targets would therefore need to be strengthened and/or the ZLEV multipliers reduced.

» Despite the relatively short lead-time, it is important to consider strengthening not only the 2030 fleet target, but also the 2025 target, and to consider annual instead of step-wise targets, because reducing CO_2 earlier has a strong impact on cumulative savings and climate efficacy and ensures a smoother technology uptake in anticipation of necessary CO_2 reductions towards 2030 and 2035.

» Any crediting scheme that awards credits in excess of reductions achieved reduces the effectiveness of the new vehicle CO_2 regulation. To avoid this effect, credits for ZLEVs and eco-innovations should be set as low as appropriate and/or phase out as early as possible. Enforcement of real-world emission reductions needs to be strengthened to ensure that any CO_2 reduction under the official test procedure is also reflected to the same extent under average real-world driving conditions. This is particularly the case for PHEVs, where the current gap between type approval and real-world performance discourages a transition towards more effective vehicle variants that show a higher electric range than is the case today. For 2030 and beyond, it is also important to also take into account differences in vehicle energy efficiency to differentiate between electric vehicles.

» Achieving a greater reduction of new car CO_2 emission levels is not a question of technology availability and cost. All technologies considered for the analysis are in principle already available today. The cost-benefit calculations, both from a consumer as well as a society perspective, are favorable in the main scenarios, especially for the years 2030 and beyond. Whether the technology market shares assumed for the scenarios will become reality depends on stringent regulatory targets, production capacities, re-charging/fueling infrastructure availability, and other external factors.

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