Greenhouse gas abatement costs for passenger cars

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Executive Summary

Transport represents almost a quarter of EU-27 greenhouse gas emissions.[1] While emissions in other major sectors such as power generation, industry, housing, and waste management are on a declining trend, transport and mobility emissions continue to rise.[1] Without accelerating emission reduction in the transport sector, the economy-wide 2030 climate targets may not be reached.

This research aims to analyse what the role and cost-effectiveness will be for renewable alternatives to reduce the emissions in the passenger car market. While answering the following research question *"What is the potential role of various renewable fuel and drivetrain options for climate action in the passenger car segment, based on their greenhouse gas emission abatement costs; how do these abatement costs change over time; and how fast and easy can these options be deployed to reduce climate emissions?"*

The greenhouse gas abatement costs of these options represent the total costs for climate emission savings for consumers and government together. Based on the understanding of the "true" greenhouse gas abatement costs of options (before policy intervention[2]), governments can decide on what options are best stimulated.

The cost analysis of greenhouse gas abatement options includes six types of powertrains and three types of renewable fuels at various blend fractions:

- Petrol car driving on E10, E20 and E85 blends of renewable ethanol
- Diesel car driving on a B30 blend of biodiesel, and B100 (FAME) or HVO100 (100% renewable diesel)
- Gas car driving on compressed biomethane
- Mild hybrid electric vehicle driving on E5, E10, E20 and E85 blends of renewable ethanol
- Plug-in hybrid electric vehicle driving on E5, E10, E20, E85 blends of renewable ethanol in combination with 100% renewable or average grid electricity
- Two types of battery electric cars driving on 100% renewable or average grid electricity

Key results

The CO_2 emission performance standard – stimulating the introduction of electric vehicles – and the proposed RED III target to reduce the emission intensity of fuels, together do not achieve enough greenhouse gas emission reduction to get on track to climate neutrality in 2050. Higher volumes of renewable fuels are required to reduce emissions in the current (and remaining) fleet of internal combustion engine vehicles.

To comply with the proposed RED III target for -13% fuel greenhouse gas intensity, the volume of renewable petrol replacements would already have to increase with a factor of 3.4 in comparison to today. To comply with the reduction of fuels' end-use emissions proposed for the extension of the Emissions Trading System to road transport and buildings, even 8 times more renewable fuels may be required in the petrol passenger car segment. Any smaller role of renewable fuels in the petrol sector would require a larger role in the diesel sector, or would require a faster path to zero emissions in the buildings sector or elsewhere in the economy.

Our analysis shows that renewable ethanol, in blends ranging from E10 to E85, has low greenhouse gas abatement costs compared to switching to other fuels or drivetrains. Therefore, renewable ethanol seems an attractive option for petrol-based passenger cars.

Other policy measures could further increase the demand for renewable ethanol. The Energy Taxation Directive could help to translate the attractive carbon abatement costs to an attractive pricing of ethanol fuel for the consumer. The Effort Sharing Regulation will force

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[1] European Environment Agency 2019, Greenhouse gas emissions by aggregated sector, Data visualisation.

[2] The market is impacted by a combination of policy interventions which cannot be singled out in the current analysis: renewable fuel mandates force fuel suppliers to sell renewable fuels at a competitive price, the CO_2 emission performance standards force OEMs to sell electric vehicles and hybrids. Batteries, materials and fuels that are imported to the EU face border taxation, and towards the future the ETS market mechanism may also apply to the transport fuels' market. The analysis in the present study only excludes final taxes (such as VAT and excise duty) and car purchase subsidies.

Member States to accelerate climate action in all sectors of the economy and as options in other sectors become exhausted, the focus will increasingly be on transport.

To increase the role of renewable ethanol in climate action in the petrol passenger car segment requires both to increase the production of Annex IX A based renewable ethanol and to facilitate the use of gradually higher blends in the existing fleet.

Recommendations for policy

- Savings achieved by the introduction of electric vehicles are insufficient to reach 2030 climate targets, and therefore additional measures are needed for the fleet of internal combustion engine vehicles that remain in the market well beyond 2030.
- Higher ethanol blends in the passenger car segment can cost effectively reduce emissions of the passenger car market. It is recommended to have a E10 blending mandate across Europe and a gradual phasing in of E20.
- A retrofit programme for part of the legacy petrol car fleet can make these vehicles suitable for E85, at a low cost. This option could be especially relevant in countries and regions where the car fleet is typically replaced at a slow pace, and where consumers cannot (yet) afford electric vehicles (or subsidies are limited) and currently rely on the second-hand market.
- Carbon abatement in passenger cars requires higher production volumes of ethanol. This can be provided by both crop based ethanol, which is currently capped under RED II, and by other renewable ethanol including advanced ethanol, produced from Annex IX A feedstock. Development of advanced ethanol requires innovation and scale, which are in turn dependent on investment certainty for the producing sector. Also, sustainable feedstock should be mobilised through targeted programs.[3]

Recommendations to the renewable ethanol producing sector

- The sector can maintain the cost-effective position of high ethanol blends by sustainably increasing the production volumes. Enough supply of alternative fuel volumes in the market lead to cost-effective options for end-users.
- To supply ethanol above the caps that limit the contribution of food and feed crop-based ethanol blends and contribute to the necessary reductions in the current fleet, it is necessary to invest in the production of advanced ethanol. The sector should demonstrate the renewable ethanol industry's ability to produce from Annex IX A feedstocks and to contribute to the minimum Annex IX A targets set by the Renewable Energy Directive, and beyond.

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[3] There is enough advanced biomass available for 50 to 100 Mtoe in EU in 2030 [Panoutsou and Maniatis 2021, Sustainable biomass availability in the EU to 2050]. The potential advanced ethanol volume amounts almost 70 billion litres in Europe in 2030 [E4Tech 2019, E20 Supply and Demand Study].

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1 Introduction

Transport represents almost a quarter of EU-27 greenhouse gas emissions.[4] While emissions in other major sectors such as power generation, industry, housing, and waste management are on a declining trend, transport and mobility emissions continue to rise.[1] Without accelerating emission reduction in the transport sector, the economy-wide 2030 climate targets may not be reached.

A combination of solutions is required to strongly reduce the climate impact from transport: curbing the demand for passenger and freight transport, increasing the efficiency of vehicles, encouraging modal shifts and shared mobility, and replacing fossil fuels with low carbon alternatives. In the passenger car segment, consumers could choose to change from an internal combustion engine vehicle to a mild hybrid[5] or a full battery electric vehicle. Alternatively, one could drive internal combustion engine vehicles on higher fractions of renewable fuels, as is stimulated with RED subtargets for renewable energy in transport.

The European Commission considers the CO_2 emission performance standards for passenger cars and vans[6] as one of the key policy instruments to reduce greenhouse gas emissions in the passenger road transport. Policies proposed in the Fit-for-55 package steer towards the introduction of 30 million electric vehicles (EVs) by 2030[7] and the discontinuation of new internal combustion engine passenger cars by 2035.[2] This makes progress in greenhouse gas emission reduction preliminarily dependent on the pace of battery-electric vehicle (BEV) adoption in the passenger car fleet.

As shown in the 2021 studio Gear Up analysis for the European Biodiesel Board (EBB),[8] the ambitions for the increased adoption of battery electric vehicles are insufficient to achieve the emission reductions required for the 2030 climate targets. A significant contribution of renewable fuels will be necessary now and remain necessary beyond the 2030-2040 decade. Of these, biofuels are readily available today and can be deployed to achieve immediate emission reductions.

This leads to the research question *"What is the potential role of various renewable fuel and drivetrain options for climate action in the passenger car segment, based on their greenhouse gas emission abatement costs; how do these abatement costs change over time; and how fast and easy can these options be deployed to reduce climate emissions?"* The current study evaluates greenhouse gas abatement options in the passenger car segment and their costs today. It assesses the current greenhouse gas abatement costs, explores future developments, and derives implications for the renewable ethanol-producing industry in a changing policy context.

The cost analysis of greenhouse gas abatement options includes six types of powertrains and three types of renewable fuels at various blend fractions:

- Petrol car driving on E10, E20 and E85 blends of ethanol
- Diesel car driving on a B30 blend of biodiesel, and B100 (FAME) or HVO100 (100% renewable diesel)
- Gas car driving on compressed biomethane
- Mild hybrid electric vehicle[5] driving on E5, E10, E20 and E85 blends of ethanol
- Plug-in hybrid electric vehicle driving on E5, E10, E20, E85 blends of ethanol in combination with 100% renewable or average grid electricity
- Two types of battery electric cars driving on 100% renewable or average grid electricity

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[4] European Environment Agency 2019, Greenhouse gas emissions by aggregated sector, Data visualisation.
[5] A mild hybrid electric vehicle combines an internal combustion engine with an electric motor. The electric motor replaces the conventional starter motor and the alternator, and recovers energy while braking. Like the full hybrid, the mild hybrid is not grid-charged (has no plug), but contrary to the full hybrid, it is never operating on the electric motor only. The electric motor only supports the combustion engine while driving, to increase fuel efficiency.
[6] European Commission 2019, Proposal (EU) 2019/631 to amend the Regulation on CO_2 emission performance standards for new passenger cars and new light commercial vehicles in line with the Union's increased climate ambition, COM(2021) 556 final 2021/0197 (COD).
[7] European Commission 2020, Sustainable and Smart Mobility Strategy, COM(2020) 789 final.
[8] studio Gear Up 2021, The role of biodiesel in EU climate action, Input for EBB roadmap to 2030 and 2050.

The greenhouse gas abatement costs of these options represent the total costs for climate emission savings for consumers and government together. Note that this differs from many other studies that explore the "total cost of ownership" of vehicle-fuel combinations. This is useful as the scale-up of greenhouse gas abatement options in the transport sector are often hindered by the associated costs for the consumers. The costs for consumers can be decreased and options become more attractive if the government applies tax exemptions and subsidies or other market measures. For instance, electric vehicles become more cost attractive in some Member States, from a total cost of ownership point of view,[9] because of purchase subsidies, decreased ownership taxes and low electricity costs. Based on the understanding of the "true" greenhouse gas abatement costs of options (before policy intervention[10]), governments can understand which options are cost-efficient and affordable and decide what options should best be stimulated. They can subsequently apply vehicle purchase subsidies, differentiate in fuel, road, or vehicle taxation, etcetera, to shift consumer behaviour towards preferred abatement options. Tax exemptions and subsidies have a cost to governments which may limit the perennity of these benefits.

By assessing the greenhouse gas abatement costs for these abatement options, new insights into the potential cost-effectiveness of switching to alternative powertrains and fuels are provided. Furthermore, strategical implications of future developments of passenger car options and the impact on required renewable fuel volumes in Europe are explored.

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[9] studio Gear Up 2021, Low-carbon mobility with renewable fuels – affordability and accessibility of passenger cars for EU, report for FuelsEurope.

[10] The market is impacted by a combination of policy interventions which cannot be singled out in the current analysis: renewable fuel mandates force fuel suppliers to sell renewable fuels at a competitive price, the CO_2 emission performance standards force OEMs to sell electric vehicles and hybrids. Batteries, materials and fuels that are imported to the EU face border taxation, and towards the future the ETS market mechanism may also apply to the transport fuels' market. The analysis in the present study only excludes final taxes (such as VAT and excise duty) and car purchase subsidies.

2 Methodology

The assessment of the cost of powertrain-fuel combinations, and the resulting current greenhouse gas abatement costs depend on scoping choices, assumptions and underlying data for vehicles and fuels. It is important to mention how these methodological choices impact the applicability of the outcomes. An extensive description of all the data used in the assessment, is given in the Annex.

Main assumptions

The main assumptions are as follows:

- Vehicle lifetime: 20 years, 250,000 km
- Depreciation over the whole lifetime: 84 %
- Electric drive share of plug-in hybrids: 75 %
- Public-to-private charging ratio for battery-electric cars and plug-in hybrids: 50/50
- Battery capacity of short-range electric car: 58 kWh
- Battery capacity of long-range electric car: 77 kWh

The underlying vehicle costs and fuel consumption data is based on the Volkswagen Golf, the most sold midsize passenger car in Europe. For each of the powertrain-fuel combinations in the study, either a Volkswagen Golf or an equivalent model (similar type, functionality, and consumer segment) from another brand were considered.

Methodological notions

Time scope of the analysis: Recent developments have significantly inflated energy prices. Therefore, the prices of all energy carriers were averaged between January 2019 and January 2021 to better reflect less disturbed market conditions. For the greenhouse gas intensity of renewables and fossil energy carriers, market-based and audited values have been used. Vehicle costs are depreciated over 20 years. The results represent the cost and climate impacts of vehicles and energy carriers in a less disturbed market, while accounting for a gradual, annualised depreciation of the vehicle investment over the vehicle's lifetime rather than steep depreciation in the first years.

Analysis of drivetrains and energy carriers combined: This allows to compare renewable fuel options in internal combustion engine vehicles with battery electric vehicles and hybrids. The analysis delivers different insights compared to studies that report on greenhouse gas abatement costs for fuels only. Especially, when switching between vehicles, the drivetrain costs can play a significant role in the abatement costs.

Taxes and subsidies are excluded. This delivers an improved insight into the "true" costs of options[11] and this is not to be confused with total costs of ownership that a consumer might experience. Apart from taxation and subsidies, other (more indirect) policy measures may impact the vehicle prices, such as the CO_2 performance standards and fuel mandates. However, the indirect impact of such policy measures on the vehicle or fuel price cannot be fully quantified and excluded, which implies that the costs presented below are still obscured by regulatory measures, market instruments etc. to some extent.

This can be useful, for instance if one wants to compare the climate gains and societal abatement costs of changing from a combustion engine car on petrol to electric vehicles, compared to introducing a low carbon fuel in that petrol combustion engine car.

Reference is petrol car driving on pure petrol: All options are compared to a petrol car driving on pure petrol. From here, the costs and benefits are calculated for either changing to higher ethanol fuel blends, different types of renewable fuels, some of which required a different vehicle, or changing to hybrid or full electric cars.

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[11] Taxes and subsidies are policy instruments to steer consumer behaviour (see introduction). The "true" costs refer to the costs excluding taxes or subsidies.

The wider scope of cost analysis especially impacts results for the diesel options. When moving from a pure petrol car to a diesel car with 30% renewables content (either FAME or HVO), a significant decrease in greenhouse gas emissions comes at a high cost, mainly because a diesel car itself is more expensive than a petrol car.

Sensitivity of results: The abatement costs are sensitive to seemingly modest variations in the costs of driving. The annual costs of all assessed options are in the range of about 2,310 – 3,100 €/year (see Figure 1 below). The most expensive option is thus 35% more expensive than the cheapest option. This means that the marginal costs of all options (compared to the pure petrol car which has an annual cost of about 2,290 €/year) are varying between about 20 and 810 €/year, which impacts the abatement costs, calculated as marginal costs (in €/year) divided by greenhouse gas savings (in tonne CO_2/year). Note that the savings per vehicle in some cases concern much less than 1 tonne CO_2/year and the marginal costs per vehicle just a few hundred euros. Uncertainties in the cost of driving therefore have a significant impact on the greenhouse gas abatement costs.

Time sensitivity of results: The calculation of carbon abatement costs is time sensitive. Purchase prices might rise or decrease and (renewable) fuel prices are constantly fluctuating. This study aims to provide a comparison between the options under current market conditions and assumptions.

3 Greenhouse gas abatement costs

3.1 Annualised costs of alternative powertrains and/or energy carriers

The results for the “true”[12] annualised costs of the considered alternative powertrain and energy carrier combinations are shown in Figure 1. They are sorted by increasing costs from left to right, ranging from 2,310 €/year to 3,100 €/year. The “true” costs represent the cost without (or rather before) subsidy or tax interventions.

Purchase costs for a large part determine the total costs, while energy costs have a limited impact

Comparing all options considered in the scope of this study, differences can mostly be seen in depreciation and insurance, both being determined by differences in initial vehicle purchase costs.[13] Typically, the energy costs, for fuels or electricity are in a closer comparable range and less decisive for the ranking of the options in the graph. Maintenance varies significantly between the combustion engine cars and the battery-electric cars, as the battery-electric powertrain vibrates less and involves fewer moving parts and is therefore expected to require less servicing.[14] Though a common assumption throughout literature,[15] more long-term knowledge on real-life performance of battery-electric vehicles is required to verify this assumption.

Lowest annual costs are observed in passenger cars driving on low ethanol blends

The annual costs are lower for most of the renewable fuels and mild hybrid (non-plugged) electric vehicles options, which are found on the left side of the graph. All ethanol blends (combustion engine or mild hybrid) are the options with the lowest costs and switching from E0 to E20 only minorly impacts the costs. In contrast, to switch from a conventional petrol car on E10 to a petrol car on E85, the cost difference is more pronounced with 260 €/year.

The plug-in hybrid and full electric vehicles are typically more expensive to buy. Short-range battery-electric cars, however, are found to be slightly cheaper than the second-most expensive combustion engine option (diesel cars on B100). All plug-in hybrids and long-range battery-electric cars populate the right side of the graph, thus being the most expensive options. The difference in costs, between the short-range and long-range electric vehicles, are caused by the battery being a significant part of the production costs of electric vehicles.

Plug-in hybrids running on E85 are found to be the most expensive option of the bunch because of the combined additional costs of making a plug-in hybrid and a flex-fuel vehicle. The additional costs to make plug-in hybrids flexible towards the use of E85 is moderate. However, the plug-in hybrids are assumed to be predominantly driven in electric mode, and thus, their cost difference to switch from E5 to E20 is negligible. The cost difference to switch a plug-in hybrid from E5 to E85 is hence also minor with only about 100 €/year extra costs.

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[12] Taxes are a major part of the total cost of ownership can be around 43% (in the example of a VW Golf in Italy as shown in our study for FuelsEurope). The ‘true’ abatement costs are not the costs a consumer would experience in Europe. Furthermore, current policy interventions are stimulating the battery electric vehicle uptake by tax exemptions and subsidies, and potentially in the near future there will be tax exemptions on renewable fuels with the proposed Energy Taxation Directive (2021/0213). These policy interventions are a cost burden to the government and researching the ‘true’ abatement costs could provide them with additional information on how to stimulate renewable alternatives and which one.

[13] The purchase prices range from 22,313 for an internal combustion engine vehicle (petrol car) to 34,941 for a long-range battery electric vehicle.

[14] ICEV has a fixed maintenance of 220 €/a (versus BEV: 118 €/a) and a variable maintenance of 19 €/1000 km/a (versus BEV: 10.1 €/1000 km/a). For the hybrids this study assumed an average between the BEVs and ICEVs. Based on formula’s derived from the 2021 study by studio Gear Up for FuelsEurope [studio Gear Up 2021, Affordability of battery-electric vehicles in the EU], especially Figures 16 and 17. For the current study, taxes (21%) are excluded and therefore extracted from the FuelsEurope values.

[15] Website Kia: “Are electric cars easier to maintain?”, retrieved March 2022 & Website U.S department of Energy: “Maintenance and Safety of Hybrid and Plug In Electric Vehicles”, retrieved March 2022

Purchase costs of BEVs depends on subsidies and market measures

This research excludes the impact of tax exemptions and purchase subsidies. In several countries, subsidy measures reduce the purchase costs of electric vehicles for consumers, which then becomes an additional cost to governments. Furthermore, the CO_2 performance standard forces car manufacturers to make battery electric vehicles cheaper than vehicles with an internal combustion engine. This effect will become stronger over time as the average CO_2 emission allowed per kilometre for new cars is further reduced by the standard. So, possibly the production costs of electric vehicles decrease over time, and their position in the graph could change, but this depends on several factors, as discussed in Chapter 4.

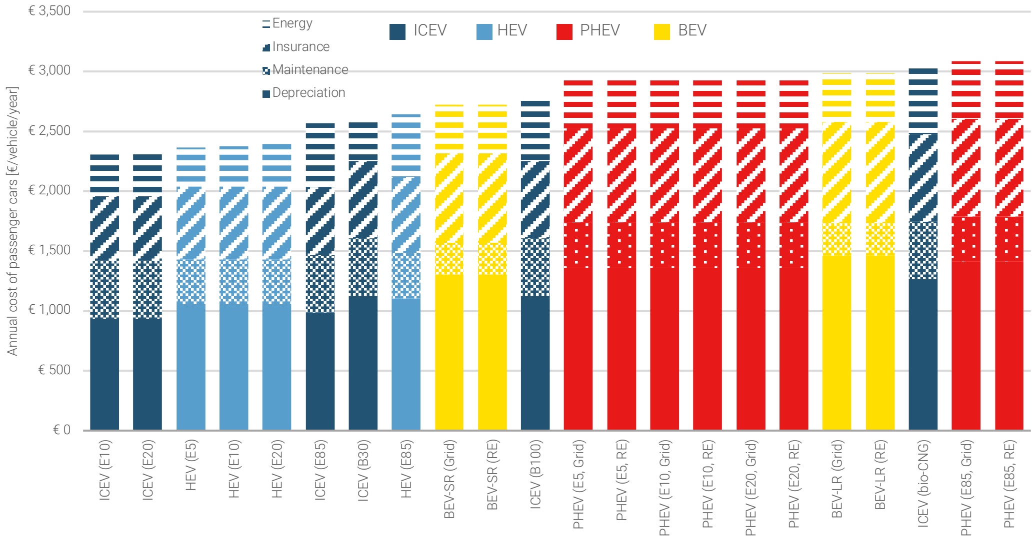

Figure 1. Annualised cost breakdown of all powertrain and energy carrier combinations excluding all taxes and subsidies. SR = Short-range (58 kWh), LR = Long-range (77 kWh), RE = Renewable electricity. For the energy costs an average was taken between January 2019 and January 2021. The depreciation is calculated with a purchase price retrieved in January 2022.

Generally, annual costs are lower for most of the renewable fuels and mild hybrid (non plug-in) electric vehicles options. Conventional and mild-hybrid petrol cars (driving on low and high ethanol blends) are the cheapest options for the assumed vehicle use profile. Increasing ethanol blends from E5 to E20 was found to only minorly affect the annual costs of all petrol powertrains.

3.2 Lifecycle greenhouse gas emission savings

The total greenhouse gas reduction potential of the considered abatement options is influenced by three independent factors:

1. Energy efficiency benefits by an alternative powertrain
2. Improved greenhouse gas intensity of the energy carrier
3. Low cradle-to-grave emissions of the powertrain

Energy efficiency results from the fuel economies of the vehicles. From low to high efficiency, the powertrains' efficiencies compare as follows: Gas-engine cars, petrol cars, mild-hybrid petrol cars, diesel cars, plug-in hybrids (for sufficiently high electric drive shares) and battery-electric cars.

The greenhouse gas intensities of the energy carriers are derived from average EU-27 data, calculated on basis of the methodology of the recast Renewable Energy Directive (RED II). Higher blends of renewables result in lower greenhouse gas intensities. B100 was found to have a similar greenhouse gas performance as pure ethanol would have if it was available as "E100" (see Table A2. Current EU-27 grid-average electricity achieves a slightly lower greenhouse gas intensity than B30. Purely renewable electricity, on the other hand, achieves a 96 % lower greenhouse gas intensity than the fossil reference. Compressed biomethane achieves on average a greenhouse gas intensity of 0 g CO_2eq/MJ. This stems from the fact that biomethane from manure is subject to a credit under the RED II from displacing methane emissions to the air from conventional manure management practices, which (in pure form) could lead to a greenhouse gas intensity of less than -100 g CO_2eq/MJ.[16] Furthermore, it is important to note that for the greenhouse gas intensity calculation of renewable ethanol and diesel the positive impact of the production of co-products is part of the RED method. Such co-products comprise for instance high protein sources (distillers' grains) that can be used for animal feed, and thereby replacing the production of animal feed and the emissions associated with this, but also other co-products used in the food value chain such as sugar and starch, or captured biogenic CO_2.

Cradle-to-grave powertrain emissions are emissions that are associated to the manufacturing and disposal of the powertrains. The cradle-to-grave climate impact of internal combustion engines is roughly equal between petrol cars, diesel cars, gas-engine cars, and mild-hybrids. However, cradle-to-grave impacts of large batteries in vehicles have been pointed out in the literature as impactful over the vehicle's lifetime greenhouse gas performance.[17] The study found that the impact of batteries in battery-electric vehicles is additional to the combustion engine powertrain cradle-to-grave impacts. Since the fossil reference powertrain has equivalent emissions to most other options presented (apart from plug-in hybrids and battery-electric cars), only the additional cradle-to-grave impact of batteries was included in the analysis (for additional information, see Annex A.3)[18].

The results of the lifecycle greenhouse gas emissions savings are presented in Figure 2. The savings are compared to a conventional petrol car driving on pure petrol and are sorted by increasing greenhouse gas savings from left to right.

Low ethanol blends reach only marginal savings; but be aware of the impact over the whole fleet

The lowest savings are achieved by the lowest petrol blend options for conventional petrol cars and mild hybrid petrol cars, however, note that the results are presented from a single car point of view, and when considering their effect on the complete fleet of petrol vehicles in the EU, higher total savings will be achieved than with most of the other options. For example, on a single car basis, bio-CNG has by far the highest potential for emission reduction per vehicle (up to 100%), especially when biomethane is produced from waste streams and their emissions are avoided. But, the share of CNG vehicles in the fleet is small and in the current European fleet savings from using bio-CNG would have a limited impact in total savings.

Due to the combination of increased vehicle efficiency and a higher renewable energy share, more than double the greenhouse gas savings can be achieved by B30 in comparison to a mild hybrid on E20. On the other hand, plug-in hybrids on low ethanol blends and grid electricity, achieve around 20 percentage-points higher greenhouse gas savings than B30 if driven electric for three quarters of their mileage.

Currently E85 achieves higher emission savings than BEVs on grid electricity

Battery-electric cars charged via the EU-27 average grid electricity mix achieve less lifecycle greenhouse gas savings than conventional petrol cars and mild-hybrids on high ethanol blends of 85 volume% bioethanol. Due to the lower energy density of E85, the cars running on E85 need to consume more fuels, which limits the greenhouse gas emission savings potential. Despite renewable electricity showing the second-lowest greenhouse gas intensity among the compared options and battery-electric cars showing the highest vehicle efficiency amongst the powertrains, the cradle-to-grave powertrain impacts remain sufficiently large

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[16] European Commission (2018) - Directive 2018/2001 Annex VI D.

[17] EEA (2018). Electric vehicles from life cycle and circular economy perspectives TERM 2018: Transport and Environment Reporting Mechanism (TERM) report

[18] Cradle to grave emissions include manufacturing: 124 kg CO_2eq/kWh and disposal: 8 kg CO_2eq/kWh. Source: Fraunhofer Institute Greenhouse for Solar Energy Systems ISE (2019). Gas Emissions for Battery Electric and Fuel cell electric vehicles with ranges over 300 kilometers - Base-case 2020.

that none of the battery-electric options achieves over 80% lifecycle greenhouse gas reductions. However, this still makes the most favourable battery-electric car (with a small battery on renewable electricity) the fourth-best option. Because of the larger battery, the long-range battery electric vehicle has higher cradle-to-grave emissions, and the vehicle is heavier, which makes the long-range vehicle less efficient compared to the short-range option. A diesel car on B100 achieves 82% greenhouse gas reduction, thereby scoring third in reduction performance. A plug-in hybrid on renewable electricity and E85 that drives three quarters of its mileage in electric mode can achieve 83% lifecycle greenhouse gas reductions.

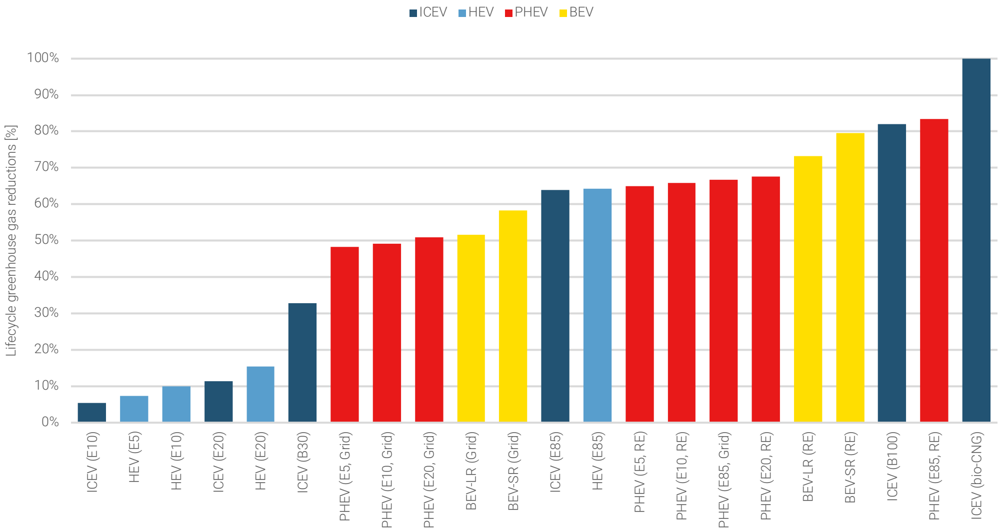

Figure 2. Lifecycle greenhouse gas emission savings for all powertrain-energy carrier combinations. SR = Short-range (58 kWh), LR = Long-range (77 kWh), RE = Renewable electricity.

The greenhouse gas of BEVs have a large margin for improvement

It is important to note that Europe's electricity grid is increasingly sourcing renewable energy to decrease its greenhouse gas intensity. If the renewable fraction of the electricity consumed by the vehicle would increase to 54% for the short-range electric vehicle or 73% for the long-range electric vehicle, these vehicles would achieve more savings than ICEVs on E85 (if these remain unchanged). In comparison, the current renewable share of grid electricity generation is 39% today.

However, Europe is rapidly expanding its battery production capacity. Europe's cleaner grid will benefit the cradle-to-grave emissions of batteries since their production is energy intensive. Similarly, the presented biofuel options can achieve lower greenhouse gas intensities, for instance by choice of feedstock, improved feedstock production or CO_2 capture. The greenhouse gas intensity target of the proposed RED III will stimulate such improvements.

3.3 Greenhouse gas abatement costs

Even though fossil petrol and low blends are the cheapest options with the highest greenhouse gas emissions, the results from the previous two sections indicate that lifecycle greenhouse gas emissions savings do not directly correlate with costs. In other words, the most climate-friendly solutions do not necessarily result in the highest costs. Therefore, the results from the previous two sections are combined to determine the greenhouse gas abatement costs.

The costs per abated tonne of greenhouse gasses is calculated by dividing the extra costs of an option compared to the fossil reference, by the achieved greenhouse gas savings:

$$\text{Greenhouse gas abatement costs} = \frac{\text{Extra costs compared to reference}}{\text{Greenhouse gas savings compared to reference}}$$

Abatement costs are relative by nature and therefore require a reference option. In this analysis, the chosen reference is a pure petrol car fuelled with "E0" petrol. The costs of the fossil reference car are 2,290 €/year, with identical values in the cost breakdown as the E10 option in Figure 1 apart from the slightly smaller energy costs. The abatement costs are highly sensitive to assumptions in the analysis.

Ethanol blends are the most cost-effective solutions; but costs will increase

The left side of Figure 3 shows that switching to different levels of ethanol mixes (E10, E20 or E85) in a gasoline car has the lowest greenhouse gas abatement costs. There are merely small differences in abatement costs when switching from E0 to E10 or E20, both are around 180 €/tonne CO_2eq. The higher cost of E20 is counterbalanced with equally higher greenhouse gas emission savings. The high ethanol blend (E85) in a petrol car has the next lowest greenhouse gas abatement costs of approximately 210 €/tonne CO_2eq. The higher fuel costs compared to E10 and E20 are also matched by equally higher greenhouse gas emission savings, but the limited additional costs vehicle also add to the abatement costs.

Note that current ethanol is mainly made from food and feed crop-based feedstocks. Larger ethanol volumes will increasingly need to come from Annex IX A feedstocks due to the current caps on food and feed crop-based biofuels. This will increase the production costs, and therefore could impact the carbon abatement cost of the ethanol options, although this will be somewhat curbed by the higher emission savings that advanced ethanol can achieve.

A strong introduction of electric vehicles reduces the size of the petrol car fleet. Still, the replacement may only be about 10% by 2030 (see analysis in Chapter 4), and ethanol is the most cost-effective solution to further decrease emissions in the remaining fleet alongside what is achieved by electrification. Moving to higher blending mandates (e.g. E10 or E20) in the remaining petrol car fleet reduces climate emissions now in the most cost-effective way.

The position of electric vehicles depends on multiple factors

Next, after the vehicle running on E85, the battery electric vehicle charged exclusively with renewable electricity or a mild hybrid running on an E85 blend have the lowest greenhouse gas abatement costs (around 280 €/tonne CO_2eq).

With an increasing renewable share in the grid electricity, the short-range electric vehicle could at some point surpass the E85 option. On the other hand, as the sales of electric vehicles increases, the drive range could become more important, which could increase the role of the long-range electric vehicle.

The position of electric vehicles in this graph further depends strongly on where the vehicles are being produced. If the batteries would increasingly be produced in the European Union, this could reduce the cradle-to-grave emissions of the vehicles (grid electricity plays a significant role in the battery cradle-to-grave emissions), but it may also make them more expensive to produce (higher labour costs and stricter conditions to health and environment than in third countries). Still, the CO_2 emission performance standard forces car manufacturers to price battery electric vehicles cheaper than vehicles with an internal combustion engine. Chapter 4 describes potential developments impacting the position of the electric vehicles compared to other drivetrain-fuel combinations.

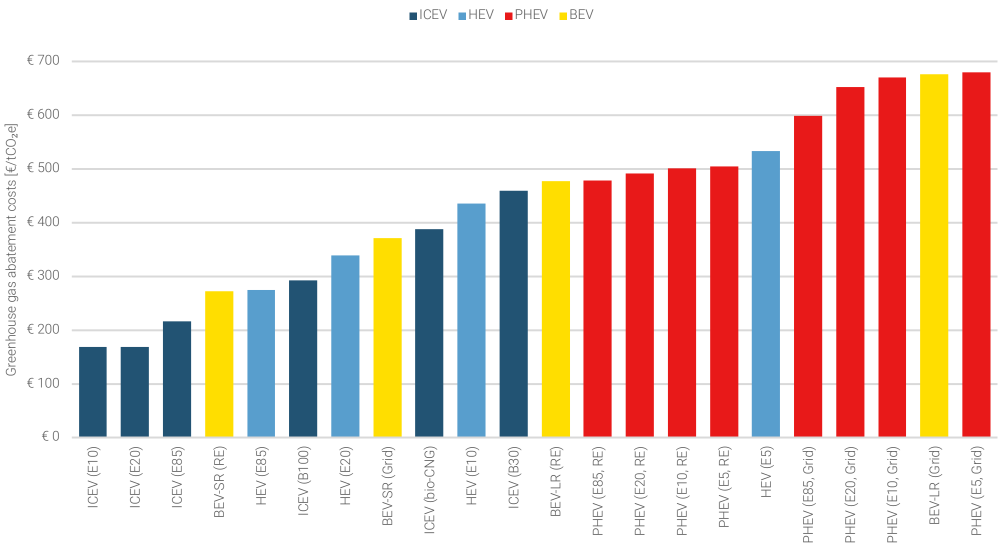

Figure 3. Greenhouse gas abatement costs of all powertrain-energy carrier combinations compared to a conventional petrol car on pure petrol ("E0"). SR = Short-range (58 kWh), LR = Long-range (77 kWh), RE = Renewable electricity. For the energy costs an average was taken between January 2019 and January 2021. The depreciation is calculated with a purchase price retrieved in January 2022.

The most expensive abatement options on the right side of the graph are plug-in hybrids and long-range battery-electric cars driving on grid electricity. Despite their low operational costs, their higher overall costs do not achieve commensurate greenhouse gas reductions as they are charged with grid electricity. The greenhouse gas emissions of grid electricity are expected to decrease in the upcoming years. Dependent on the cost developments of batteries and whether manufacturers will revert to lower battery capacities again, greening the grid has the potential to shift them more to the left side of the graph.

Near future improvement of grid greenhouse gas intensity has small impact on the relative ranking of options

Figure 4, below, shows the impact on the greenhouse gas abatement costs and the ranking of options, when the greenhouse gas intensity of grid electricity is reduced. In 2030, the share of renewable energy in electricity generation will be around 70%, and, consequently, the greenhouse gas intensity will have decreased to 114 gr CO_2/kWh.[19] We have kept other parameters constant.

For the short-range electric vehicle, the greenhouse gas emission abatement costs decrease with around 70 €/tonne CO_2eq. The mild hybrid running on E20 moves one place to the right but remains cheaper than a gas vehicle running fully on bio-CNG (since the result for both has not changed). The plug-in hybrid running on a mix of grid electricity and E85 moves three places to the left and decreases the greenhouse gas abatement costs by around 60 €/tonne CO_2eq. The other plug-in hybrids running on E20, E10 and E5 also decrease in costs, but slightly less than the long-range battery electric vehicle running on grid electricity. In conclusion, the mutual position of renewable alternatives may change in the near future, due to a better performance of hybrids and short-range electric vehicle running on grid electricity. The performance of the long-range electric vehicle is still determined by the higher cradle-to-grave emissions, but this might also decrease soon, depending amongst others on where the battery and vehicle are being produced.

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[19] European Environment Agency (EEA) website. Greenhouse gas intensity of electricity generation in Europe. Article was published in 2021 and data was retrieved in March 2022.

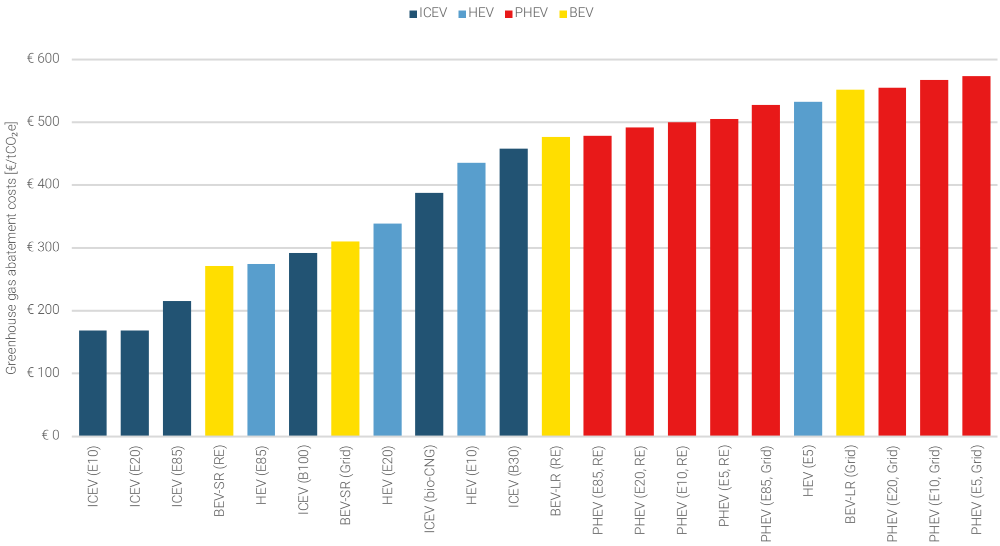

Figure 4. Greenhouse gas abatement costs of all powertrain-energy carrier combinations compared to a conventional petrol car on pure petrol ("E0"), assuming that the EU electricity grid contains 70 % renewable energy (as aimed for by 2030). SR = Short-range (58 kWh), LR = Long-range (77 kWh), RE = Renewable electricity. For the energy costs an average was taken between January 2019 and January 2021. The depreciation is calculated with a purchase price retrieved in January 2022.

Increasing renewable shares is a cost-effective solution for all powertrains

Figure 5 shows the relation of the greenhouse gas emission savings of the different powertrain/energy carrier options, to the renewable fraction in the energy carrier, and the result for the abatement costs. The size of the balls represents how much greenhouse gas emissions the options are saving. The x-axis represents the renewable share in the energy used by the vehicle, and this allows to understand how options improve when the fraction of renewable electricity in the grid increases, or when higher blends of renewable fuels are used.[20] The resulting abatement costs are plotted on the y-axis, so the higher the position, the more expensive the option is. Per powertrain option, balls are connected to show the impact of switching to higher renewable energy share on the greenhouse gas savings and the greenhouse gas abatement costs.

For the gasoline car the greenhouse gas abatement costs slightly increase, when the renewable energy share increases. However, when looking at all the alternatives in the model, the greenhouse gas abatement costs are always the lowest for a gasoline car driving on ethanol blends. While greenhouse gas saving per vehicle that can be achieved with E10 and E20 is limited, the savings on the whole fleet can be considerable. Currently the average in Europe is an E6.5 blend. Moving to E10 would reduce the total greenhouse gas emissions of the passenger car petrol segment with 2%, and moving to E20 would reduce it with 7.8%. Going from E10 to E20 and E85, higher blends achieve much more savings per vehicle while the abatement costs only increase marginally. Towards 2030, as passenger cars should achieve a sharp reduction in greenhouse gas emissions (see Chapter 4), higher blends will be needed across the passenger car fleet. Therefore, for ethanol to remain a relevant option, it should move to the right-hand side of the graph and to the larger bubbles.

For most powertrains (both the hybrids, electric vehicle and diesel vehicles) the greenhouse gas abatement costs drop, when the renewable energy share (and therefore the emission saving) increases. For these options, it is logical to switch to higher renewable energy blends, both from the climate and the cost effectiveness point of view.

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[20] For example, E85 has 85% renewable share on basis of volume, but 79% energy percent. For the hybrid electric vehicles (mild and plug-in), the fraction of renewable energy in hybrid options is taken as the weighted average of electricity and renewable fuels, while also considering that the electric share in the kilometres is more efficient than the fuel share. Therefore, a PHEV that runs for 75% on grid electricity with 20% renewables, and for 25% on E85 (with 79% renewables) is placed at 52%.

Similar to how high ethanol blends have a positive climate impact in gasoline cars, they also decrease greenhouse gas emissions in plug-in hybrids and mild hybrids, without further increasing the abatement costs. The combination of high ethanol blends in plug-in hybrids leads to higher savings than when used in gasoline cars or mild hybrids, because of the combined effect of the lower carbon intensity of the fuels and the electric driving, but obviously at a higher cost because the vehicle is more expensive (as discussed in Section 3.1). Mild hybrid vehicles driven on ethanol blends initially have considerably higher abatement costs, while the advantage of hybridization for the total savings is limited. The abatement costs of the mild hybrid on E85 approach the costs of the regular ICEV on E85. At this point, the savings achieved by renewable energy (almost) become more important than the high cost of the hybrid technology.

Finally, we observe that short-range electric vehicles achieve high savings in all cases, even when driving on grid electricity with just 39% renewable electricity. However, the abatement costs are higher than those of than those of ethanol in ICEVs. For the annual mileage assumed in this study, long-range electric vehicles achieve almost the same savings as short-range electric vehicles but at considerably higher costs.

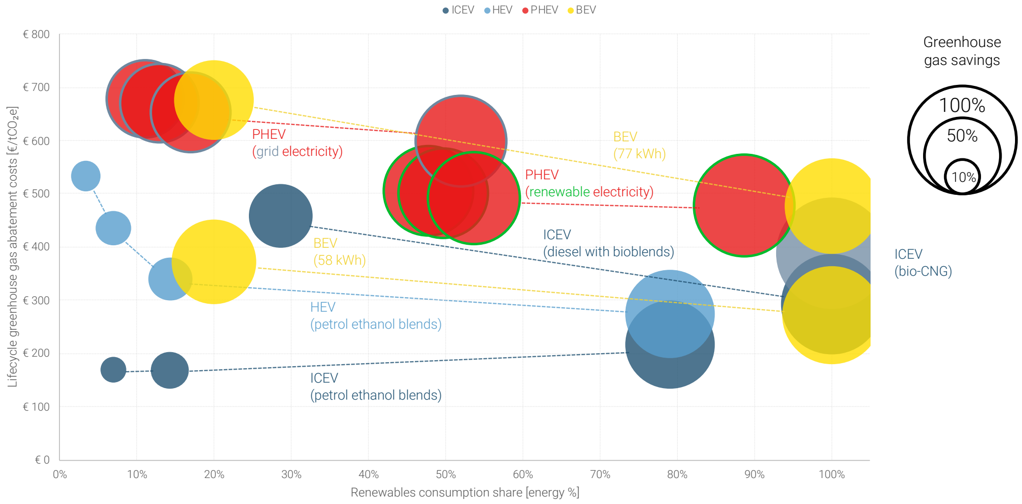

Figure 5. The amount of greenhouse gas savings and abatement costs per option, as a function of the share of renewable energy. For the energy costs an average was taken between January 2019 and January 2021. The depreciation is calculated with a purchase price retrieved in January 2022.

There are substantial greenhouse gas emission savings to be reached within our current fleet, when switching to higher ethanol blends without a substantial increase in (greenhouse gas abatement) costs. Where, higher ethanol blends have the lowest greenhouse gas abatement costs. Higher ethanol blends show great potential to reduce greenhouse gas emissions of hybrids, when they use grid electricity and renewable electricity. Switching to higher ethanol blends is currently the most cost-effective solution to reach greenhouse gas emission savings. The increasing renewable share in grid electricity will move the battery electric vehicle on grid electricity to the right and slightly downwards in the graph.

In conclusion, switching to higher ethanol blends is a cost-effective solution to reach greenhouse gas emission savings in the current fleet, even before drastically changing taxation. The proposed Energy Tax Directive aims for lower tax tariffs for renewable fuels of Annex IX A and IX B feedstocks, which could ensure these relatively low greenhouse gas abatement costs for high ethanol blends also become attractive for consumers.

4 Future developments

4.1 The impact of policy instruments

In the analysis of the passenger car options in Chapter 3, taxation and subsidy measures have been left out to be able to compare options on basis of their greenhouse gas abatement costs today. Future prices cannot be predicted, but some assumptions and predictions could be made on basis of the instruments proposed by the European Commission, such as taxes and policy instruments that are part of the Fit-for-55 package published in July 2021.

A previous study of studio Gear Up[21] has shown how policy instruments are a substantial factor in how renewable options compare on basis of total costs of ownership. Figure 6 shows an example, the options for a consumer in France with a Volkswagen running on either E5 or B7 who could decrease greenhouse gas emissions by switching to high fractions of renewable fuels, such as E85 (in an adapted engine) or 100% HVO respectively. A switch to a comparable battery-electric model achieves greenhouse gas emission savings against lower annual costs of ownership due to the several benefits for battery-electric vehicles in the French market.

The comparison includes both the average grid-electricity mix in the EU-27 and the electricity mix in France, with a high share of nuclear. In absence of vehicle purchase subsidies for electric vehicles (el-EU27-ns/elRE100-ns) the (comparable) vehicle running on E85 has lower total costs of ownership (the analysis includes energy and vehicle ownership taxes). However, with subsidies applied (el-EU27-s/ el RE100-s) the electric model becomes cheaper for a consumer in France, on basis of the total costs of ownership.

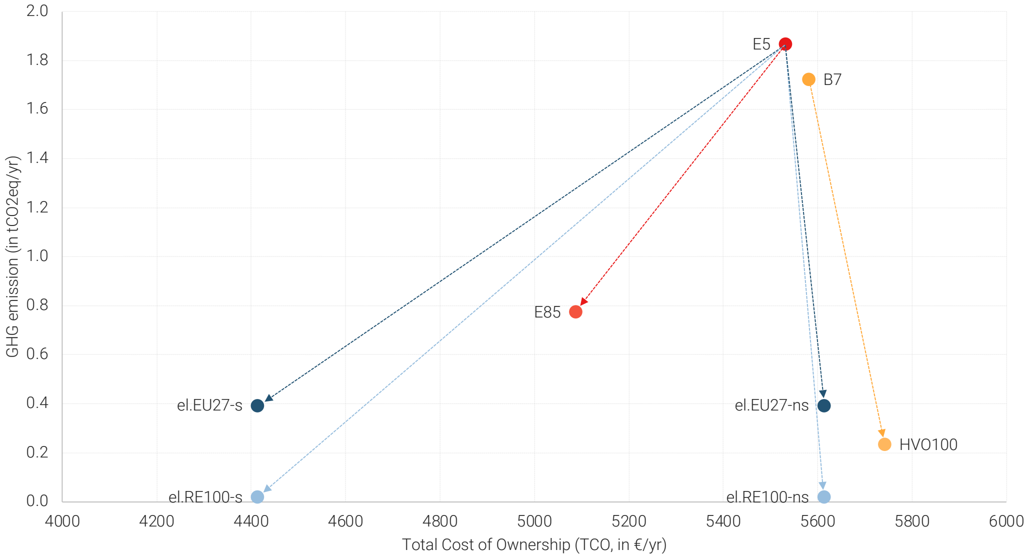

Figure 6. Previous TCO analysis of an ICEV on 100% renewable fuels (E85/HVO) with a comparable BEV-model in case of vehicle purchase subsidy (-s) and no vehicle purchase subsidy (-ns), but including taxes [studio Gear Up 2021, Low-carbon mobility with renewable fuels – affordability and accessibility of passenger cars for EU, report for FuelsEurope].

The previous studio Gear Up analysis shows that the level playing field changes if options receive, or do not receive equal subsidies (on basis of a total cost of ownership analysis). Also, a recent TCO-analysis performed by studio Gear Up[22] and a recent Fraunhofer study[23] make clear that taxes and policy incentives translate in substantial factors influencing future

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[21] Comparison on the total cost of ownership of internal combustion engine and battery electric vehicles in sixteen European Member States, including and excluding subsidies [studio Gear Up 2021, Low-carbon mobility with renewable fuels – affordability and accessibility of passenger cars for EU, report for FuelsEurope].

[22] Studio Gear Up, 2022, 'To drop-in or to adapt the engine?' Comparing total cost of ownership of renewables in heavy-duty trucks.

[23] Müller-Langer, 2022, Presentation by Fraunhofer Institute: "Impacts of an emissions trading system in transport for the economic viability of e-mobility?" at the Fuels of the Future conference on the 24th of January in 2022.

prices of energy for transport. This demonstrates how policy instruments and incentives will influence the competitiveness of the options in the market.

To assess the most “cost-effective” technologies to defossilise the petrol car segment in the near future, it was assumed that greenhouse gas emission reduction goals such as set in the European climate law have to be met under all circumstances. To achieve this target, the market development of the battery-electric option, and the policy incentives towards various alternatives determine the demand of renewable alternatives. Possible effects of these two important external drivers are explored below.

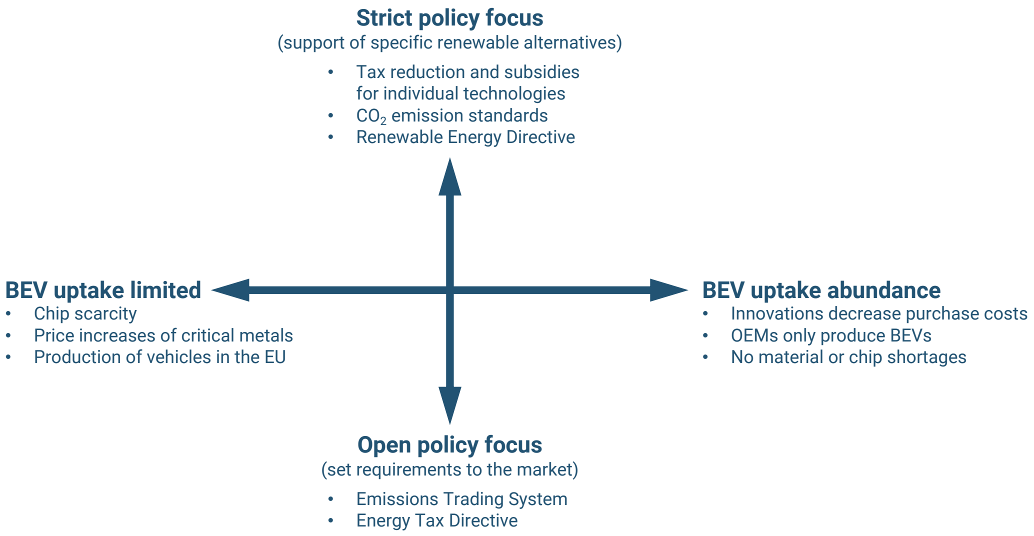

Figure 7. Overview of the four different scenarios on basis of two developments: the market development of the battery-electric option (horizontal axis) and the policy incentives towards various alternatives (vertical axis).

The policy-drivers explained

Open Policy Focus

An Open Policy focus can make room for multiple solutions and set certain requirements to the market, without highlighting a single technology to achieve the climate goals. This happens when a policy instrument such as the emissions trading system is reducing the total fossil emissions allowed from a whole sector in a steady reduction pathway to zero, without benefiting certain solutions over other solutions. Options in the market then compete on basis of greenhouse gas emission abatement costs. This can be seen as a ‘pull’ scenario in which the market will develop solutions to reach the policy targets.

Technology strict policy

The opposite of the Open Policy focus is a Technology-Strict Policy focus, where certain technologies are preferred by policy makers, and the policy support is directing towards these solutions, as articulated by the European Commission in its Sustainable and Smart Mobility Strategy. European policy aims for zero-emission mobility which translates for passenger vehicles in stimulating battery-electric vehicles with a set of instruments. The CO_2 emission performance standards are meant to regulate new sales, ultimately leading to selling only passenger vehicles with zero tailpipe emissions. The Alternative Fuels Infrastructure Regulation (AFIR) further supports the development of the electric energy and hydrogen infrastructure for these policy-prefered options, while other renewable alternatives for the road sector are not stimulated. Due to the policy direction towards electric mobility; many member states offer purchase support measures for electric vehicles such as road tax rebates, purchase subsidies; and zero-emission zones are introduced at local levels. At the same time, mandates for renewable fuels (e.g. E5, E10 or B7) make sure that also in the existing car park greenhouse gas reductions are realised. The CO_2 emission standards and the renewable energy mandates can be considered as ‘push’ mechanisms.

Potential electric vehicle market developments in the near future

The availability and cost of electric vehicles in the European market depends on several factors. Especially the battery is a crucial factor: some materials for the current battery (especially lithium, cobalt, nickel, and manganese) are constraint in supply, resource sustainability impacts need to be reduced and this will have a cost, the increasing (global) demand will increase prices, production in the EU (as many policy makers would like to see) will increase the price of batteries that are currently assembled in third countries mainly.

On the other hand, innovation and mass adoption are expected to decrease production costs and sales prices. The maximum battery capacities and electric ranges increased significantly over the past decade, and this makes battery-electric vehicles a more attractive and accepted option for a wider public. With the announced production upscale of new "gigafactories" for battery-electric vehicles, as well as strong policy support, the prices of electric vehicles may decrease in the upcoming years. Research and development of alternative cell chemistries could reduce the current dependence on metals and, consequently, improve sustainability and reduce prices.

This implies that the cost development of electric vehicles is difficult to predict. If the availability of battery electric vehicles is abundant and the prices are low, then the deployment of electric vehicles may take place automatically and faster than the CO_2 emission performance standard requires. However, if prices rise due to material scarcity or other factors it can be expected that the BEV uptake will be limited, and the CO_2 emission performance standard will be difficult to meet. In a strict policy focus situation, governments may compensate the high prices with tax exemptions or subsidies.

Consequences for the role of renewable fuels

In general, the market developments of battery electric vehicles and the proposed instruments of the Fit-for-55 package could impact the required volumes of ethanol and other renewable alternatives towards 2030. However, the scenarios show that both renewable fuels and electric vehicles are needed to reduce the emissions of the passenger car segment. How significant the role of ethanol will be, depends on the policy landscape and how much emission reduction can be achieved by electric vehicles in the fleet. This is further assessed in the next section.

4.2 Fleet electrification alone does not timely achieve climate emission reduction in passenger cars

The proposed Fit-for-55 measures will sharply increase the demand for renewable alternatives in the passenger car segment between now and 2030 and far into the 2040s to meet the climate targets and the emissions trading system capping the amount of fossil fuels that can be used.

One of the proposed Fit-for-55 measures targets lower CO_2 emission standards for new passenger vehicles. The average emissions of new cars were 95 g CO_2/km in 2020 and shall decrease to 81 g CO_2/km in 2025 and to 43 g CO_2/km in 2030. Thereafter, they shall rapidly decrease to 0 g CO_2/km in 2035. If met, the proposed CO_2 performance standards would lead to a share of about 14% electric vehicle equivalents on the road by 2030,[24] or about 36 million if the total fleet does not grow substantially.

However, even though new cars emit only 43 g CO_2/km on average by 2030, the average emission performance of the total fleet largely depends on the legacy fleet (see Figure 8) as the new vehicles only slowly replace the existing ones.[25] The average emission performance

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[24] In fact, the required average emission profile may be achieved by combinations of electric vehicles, other zero emission vehicles, (plug-in) hybrid electric vehicles and more efficient internal combustion engine vehicles. This may mean that less than 36 million electric vehicles are needed to achieve the same effect, if other cars also reduce their emission profile. This does not impact the emission graphs or, consequently, the demand for (renewable) fuels. Note that the European Commission stated that there would be 30 million battery-electric and fuel cell vehicles by 2030.

[25] In this study, an average replacement rate of 4 % is assumed.

of the complete EU passenger car fleet will have to decrease from about 120 g CO_2/km today to about 103 g CO_2/km in 2030. The real average emissions of the fleet will remain even higher in 2030 because electric-car sellers earn “supercredits” that count double on the target of the CO_2 performance standards for new cars. In other words, the red line in Figure 8 depicts a political measure that will differ from real-life achievements. For the purposes of this study, however, the effect of supercredits was neglected. Faster electrification to significantly decrease the fleet CO_2 emissions requires a mix of higher sales shares of electric vehicles and higher fleet turnovers (e.g. by scrapping mechanisms targeted towards combustion-engine vehicles).

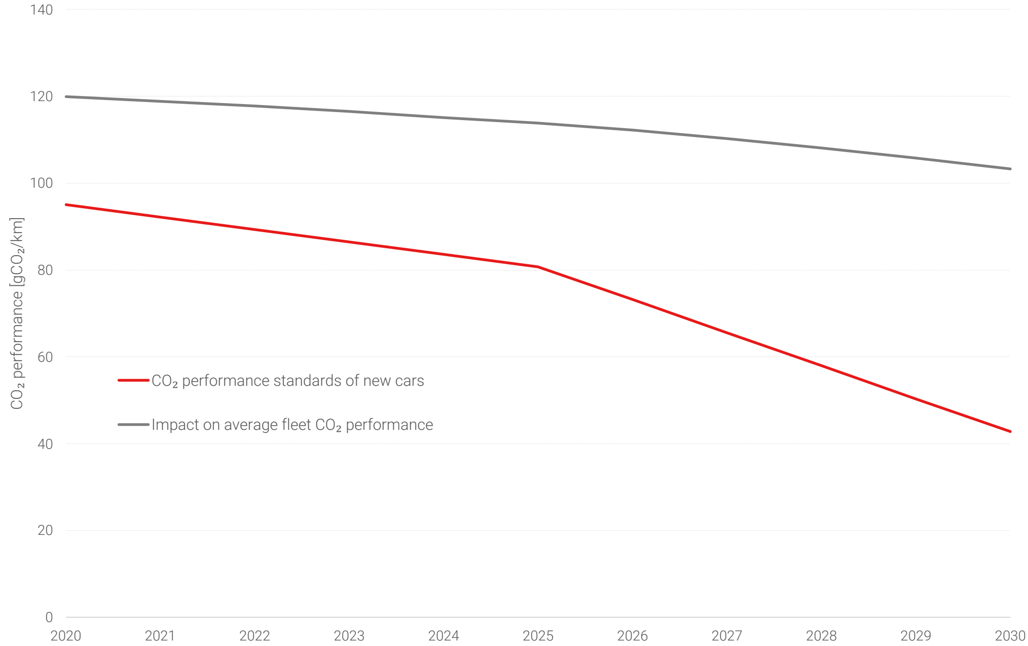

Figure 8. Impact of the proposed CO_2 performance standards for new cars (red) on the average CO_2 performance of the total EU-27 fleet (grey). The currently legally binding CO_2 performance standards envision a reduction of 15 % in 2025 compared to 95 gCO_2/km reached in 2020. The Fit-for-55 proposal amended the previous 2030 ambition and increased it to a reduction 55 % compared to 2020. An annual fleet renewal rate of 4 % was assumed. The effect of supercredits was neglected for the purposes of this study.

While Figure 8 depicts the decreased CO_2 emissions per kilometre, it is important to understand the growth in driven passenger car kilometres to understand the impact on overall passenger car emissions. If passenger car transport in the Covid-impacted year 2020 had been an interpolation of passenger car transport between 2015 and 2025 projections, about 4.2 trillion (10^{12}) passenger kilometres (pkm) would have been driven in the European Union. In 2025, this value is projected to increase to 4.4 trillion pkm and in 2030 to 4.6 trillion pkm. Therefore, overall passenger car transport demand is expected to grow by about 9.6 % (neglecting the dip caused by Covid-19). Multiplying this demand in kilometres with the fleet's average CO_2 performance per kilometre (grey line in Figure 8), one can estimate the total CO_2 emissions of the passenger car fleet (Figure 9).

Figure 9 below shows that the policy trajectory for the CO_2 emission performance standard leads to 14% reduction of tank-to-wheel emissions (grey arrow) in the passenger car segment compared to what the current fleet would emit at the 2030 demand if they were fuelled entirely by fossil fuels. Due to the increasing demand for transport, the overall tank-to-wheel emissions only decrease with 6% compared to 2020.[26]

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[26] It should be noted that for simplicity, this analysis disregards the impact that Covid-19 caused on the emissions of passenger car mobility. Instead, 2020 demand levels from the EU Reference Scenario 2020 were interpolated between 2015 and 2025 to estimate the emissions, if the Covid-19 pandemic had not happened.

Besides the effect of introducing electric vehicles, mandates may increase the volumes of renewable fuels from about 4% in 2020 to 14% in 2030[27], which leads to another 12% reduction in tank-to-wheel emissions (green arrow) due to the overall increasing energy demand.[28]

Furthermore, Fit-for-55 proposes to establish ETS for road transport (together with buildings), which would put a firm ceiling to end-use emissions in the road transport sector. Figure 9 outlines how the overall policy target and the ETS trajectory would require a significant further decrease of tank-to-wheel emissions by 2030 (orange arrow). The illustrated ETS trajectory assumes that emissions in road transport and buildings would have to decrease in the same speed, where it should be noted that the endpoint for both sectors together is zero emissions by about 2044. Furthermore, it was assumed that within road transport, emission reductions in all subsectors (i.e. light-duty, medium-duty and heavy-duty road transport) would proceed at the same pace.

The analysis assumes a pro rata contribution of petrol and diesel replacements in the passenger car segment, a pro rata contribution of passenger cars in the (road) transport segment (both for ETS and RED III targets) and a pro rata contribution of road transport in the proposed ETS for road transport and buildings.

Of course, the relative contribution to the overarching goals could be smaller or larger. It is important to note that (in terms of end-use CO_2 emissions) road transport emits about two times more CO_2 than buildings, which, irrespective of where emission reduction is cheapest, means that road transport cannot delay emission reduction for much longer in the frame of ETS. Within transport, road transport is by far the largest emitter, and passenger cars represent about two thirds of the energy consumption. Any smaller contribution of road transport to achieving the RED III target, would require a disproportionate contribution from aviation and maritime.

All in all, this means that about half of the energy in EU transport is consumed by passenger cars, and these cars therefore must play an important role in emission reduction in the transport sector. Increasing sales of electric and other zero emission vehicles will strongly reduce the demand for fuels, but only from about 2040 onwards (see our previous analysis[29]).

The passenger car segment consists of approximately 55% cars driving on diesel and 45% cars driving on petrol. While it is possible to realise higher mandates in the diesel segment, this would require mainly high blend diesel replacements that increasingly will need to be based on Annex IX A type feedstocks or are made from renewable electricity, due to the cap on food and feed crop-based biofuels and the cap on the use of Annex IX B type feedstocks. The petrol segment represents an important option in realising higher renewable fuels mandates for the market, especially since ethanol presents a cost-effective option for society as was shown in Chapter 3.

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[27] These percentages concern the broadened scope (incl. international aviation and maritime) of the amended Renewable Energy Directive, as proposed as part of the Fit-for-55 package.

[28] The greenhouse gas intensity reduction target by the proposed amended Renewable Energy Directive (RED III) is -13 %. However, also renewable electricity provided to electric vehicles can count towards this target and counts double. Assuming that 4 % of this reduction will be achieved by renewable electricity, then the remaining 9 % greenhouse gas intensity reduction will require about 12 % renewable fuel volumes of on average 75 % greenhouse gas intensity reduction.

[29] By 2030 only about 15-20% of the passenger car fleet consists of electric vehicles, while the total demand for transport still increases, by 2035-2040, electric vehicles become dominant and curb the energy demand [studio Gear Up 2021, The role of biodiesel in EU climate action. Input for EBB roadmap to 2030 and 2050].

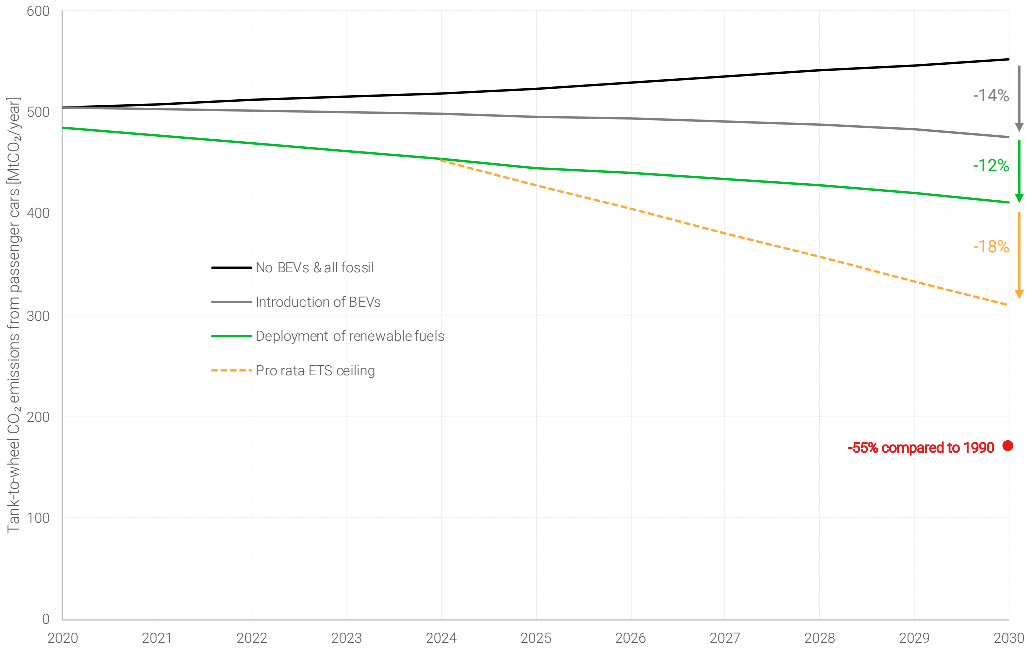

Figure 9. Tank-to-wheel emission development in the transport sector, and how emissions decrease thanks to the introduction of BEVs and renewable fuels. The achievement is compared to a possible ETS trajectory for road transport and buildings, and the economy wide -55% target of the Fit-for-55 policy package, both assuming that passenger cars would contribute pro rata to a required overall emission reduction in the transport sector and the ETS for road transport and buildings.

The path to climate neutrality in the EU is specified in various ways. The overall Fit-for-55 goal is to economy wide achieve 55% emission reduction by 2030. Many sectors have already achieved a significant emission reduction since 1990 and additional reduction becomes increasingly expensive. Emissions from transport have increased between 1990 and 2020 and it is necessary that transport at least contributes its share to the emission reduction. This is in particular the case in relation to the Effort Sharing Regulation that sets binding national targets for EU Member States. If emissions in the national mobility sector remain too high, other economic sectors must counterbalance by reducing greenhouse gas emissions even stronger. The lack of progress in reducing road transport greenhouse gas emissions is therefore increasingly putting pressure on the other economic sectors, with the effect that national Effort Sharing Regulation targets are increasingly difficult to be reached.

Again, this shows the need for additional volumes of renewable fuels additional to the RED mandates. The following section provides argumentation on how this will impact the position of renewable petrol replacements such as ethanol.

4.3 The role of renewable petrol replacements should increase sharply to achieve climate targets

Assuming an equal share in the deployment of mandated renewable fuels in the diesel and petrol segment, then this would imply that the implementation of the RED III -13% emission intensity target could require about 5 times the amount of renewable fuels in petrol cars in 2030 compared to 2020. If somehow deployment of these higher volumes would not take place in the diesel segment (or vice versa), this amount will have to be higher. Having in mind the emission ceiling of the ETS for road transport and buildings, the volume of renewable fuels in petrol cars in 2030 could even be twelve times higher than in 2020. Figure 10 illustrates this gap between the amount of renewable petrol replacements required in passenger cars until 2030, according to RED III and according to a linearly decreasing ETS ceiling (based on several pro rata assumptions as previously explained: the combined sectors of road transport and buildings have to reduce their emissions in the same pace; passenger cars and heavy-duty vehicles have equal shares of renewable fuels; and diesel and gasoline vehicles contribute equally).

However, petrol demand itself is projected to grow by about 50% between 2020 and 2030 (partially due to the decreased demand in 2020 caused by the Covid-19 pandemic). Hence, the renewable energy volume in petrol would need to increase with a factor of 3.4 to comply to the -13% target of the RED III, or a factor of 8 for ETS compliance. If for instance on average 6.5 volume % of petrol were substituted by ethanol in 2020, this value would have to increase to 20.5 volume % for RED III compliance (possible e.g. via an E20 mandate and small additions of drop-in petrol), and to about 43.6 volume % for ETS compliance (possible via E85), both by 2030.

However, other renewable petrol substitutes such as drop-in petrol (e.g. via Methanol-to-Gasoline) or bio-naphtha could also contribute to meeting the renewable petrol demand. Alternatively, renewable substitutes for diesel could progress faster than renewable petrol substitutes. However, there are limits to the growth of renewables in the diesel segment. Volumes of renewable substitutes for diesel in road transport have to more than double under the Fit-for-55 ambitions by 2030, both in absolute and in relative terms. If the share of ethanol in petrol remains constant between 2020 and 2030, diesel substitutes would have to triple instead, leading to a blend requirement of over 25% by 2030.

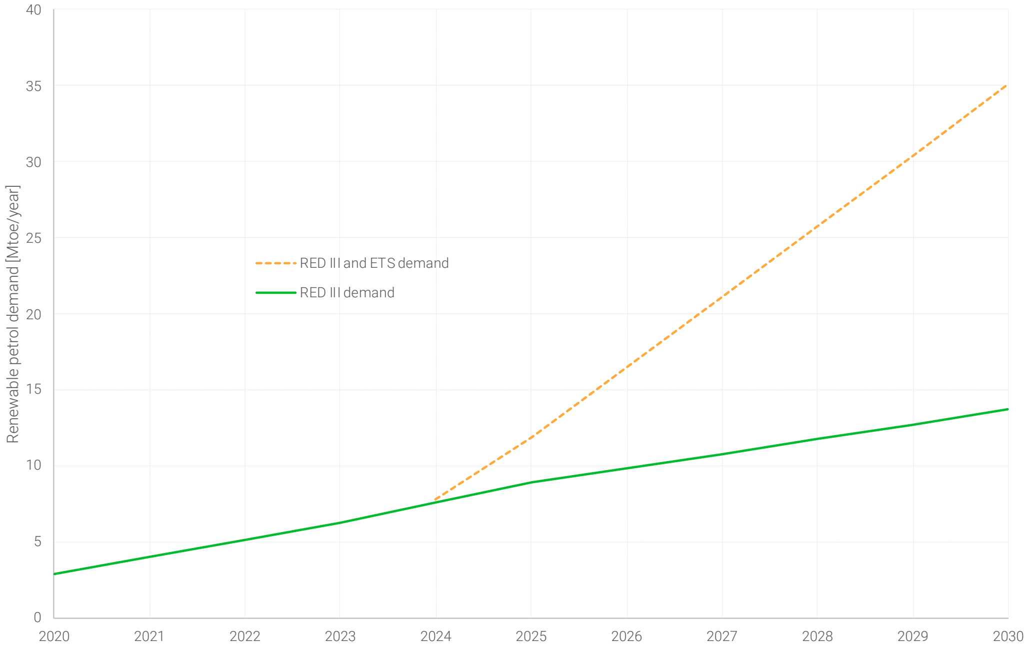

Figure 10. Development of the demand for renewable petrol replacements, assuming that the required RED III -13% emission reduction is equally achieved in all road transport subsectors, that the ETS for buildings and road transport requires an equal contribution by both sectors as well as transport subsectors, and assuming an equal share of renewable fuels in diesel and petrol driven passenger cars.

If renewable petrol demand is not meeting the targets, there are a couple of other measures to reach the required emission savings: limit mobility, modal shift measures, higher renewable diesel substitute blends, scrapping measures to turn over the car fleet quicker et cetera.

Current policy interventions reduce passenger car emissions by bringing new electric vehicles to the market. However, the study of studio Gear Up for FuelsEurope shows that the passenger car fleet is expected to grow as well and part of the new electric vehicles are an addition to the fleet, rather than replacing it.

Figure 11 shows that when battery electric vehicles replace gasoline vehicles, an increasing share of ethanol further reduces fossil fuel consumption and decreases emissions in the remaining fleet. In conclusion, battery electric vehicles and ethanol blends can work complementary to reduce fossil fuel dependency. An economy wide application of E10 or E20 would have a significant impact alongside the introduction of electric vehicles. Lowering the volumes of ethanol would not make sense with the challenges of reducing emissions in the passenger car segment.

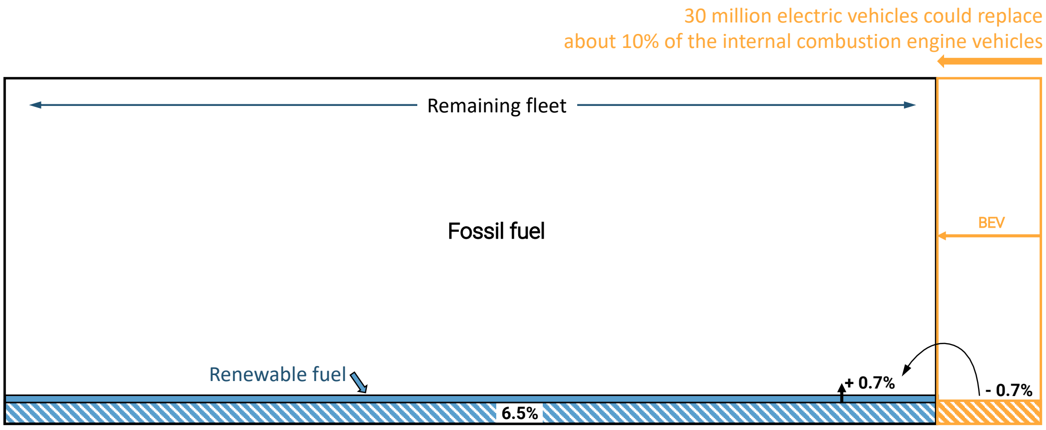

Figure 11. The impact of replacing 10% of the petrol cars with electric vehicles on the blend fraction of ethanol. Currently, the fraction of ethanol is about 6.5%. When 10% of the vehicles is replaced with electric vehicles, 10% of that 6.5%, or 0.7% would no longer be used. To place the same ethanol volume in the market, the blend level should at least be increased to 6.5%+0.7% = 7.2% in that smaller fleet.

4.4 Targets require high volumes of advanced ethanol and application in higher blends

As argued above, the RED III -13% target may require 3.5 times more renewable petrol replacements in the passenger car segment by 2030 compared to today. To get on track for climate neutrality in 2050, the ETS ceiling would require even 8 times more. And if the -55% in 2030 would also have to be achieved in transport, it would even be almost twice the amount that is required for a pro-rata ETS. All in all, this means that a large amount of ethanol may be needed to achieve European climate targets, with the exact amount depending on how successful other sectors (buildings), electric vehicles, and other renewable fuels are.

As shown in Chapter 3, ethanol is the most cost-effective solution to reduce emissions in multiple powertrains and to comply to the proposed policy targets. The current and near future fleets still mainly consist of petrol and diesel cars, and thus, much larger volumes of renewable fuel replacements are needed. These renewable petrol replacements will for a large part concern renewable ethanol, and therefore larger volumes of renewable ethanol will be needed. This can be provided by both crop-based ethanol, which is currently capped under RED II, and by other renewable ethanol including advanced ethanol, produced from Annex IX A feedstock. Development of advanced ethanol requires innovation and scale, which are in turn dependent on investment certainty for the producing sector. Also, sustainable feedstock should be mobilised through targeted programs. In case of an Open Policy focus, with a focus on market instruments such as ETS and ETD, advanced ethanol will be most cost effective to reduce emissions from the remaining petrol car fleet.

Current mandates are focusing on E5 and E10 blends for the current fleet. It is recommended to gradually increase the mandates to E20 to reach the proposed RED III emission reduction target in the current fleet. To further increase the role of ethanol, E85 flex-fuel retrofits should be considered in parts of the petrol fleet that are most challenging to replace with electric vehicles. Retrofits could become part of a wider subsidised fleet renewal scheme to quickly increase the number of E85-capable vehicles on the road. An established European emission norm for E85 would further contribute to decreasing costs. The additional flex-fuel vehicles can contribute faster to achieving the greenhouse gas emissions required by the ETS. Especially in countries, where the passenger car market is dependent on the second-hand market (which for a long time will largely consists of internal combustion engine vehicles) and in countries were subsidies for new electric vehicles are limited.

5 Conclusion and recommendations

While emissions in other major sectors such as power generation, industry, housing, and waste management are on a declining trend, transport and mobility emissions continue to rise. Thus, reducing transport emissions is increasingly relevant in combatting climate change. Multiple policies and targets were proposed under the Fit-for-55 package to reduce emissions in the passenger car segment.

For example, the CO_2 emission standards is an effective instrument to incentivise the uptake of battery electric vehicles, however this policy only targets new vehicles coming to the market. Since vehicles in the EU have a lifetime of 20-25 years, the introduction of electric vehicles is slow process, and this does not quickly enough decrease the greenhouse gas emissions of the whole passenger car segment. Faster electrification to significantly decrease the fleet CO_2 emissions would require a combination of higher sales shares of electric vehicles, from today onwards, and higher fleet turnovers (for instance with programs to actively take internal combustion engine vehicles from the fleet).

This research aimed to analysis what the role and cost-effectiveness would be for renewable alternatives to reduce the emissions in the passenger car market. While answering the following research question *"What is the potential role of various renewable fuel and drivetrain options for climate action in the passenger car segment, based on their greenhouse gas emission abatement costs; how do these abatement costs change over time; and how fast and easy can these options be deployed to reduce climate emissions?"*

Key results

Higher volumes of renewable fuels are required to reduce emissions and follow the trajectory of the proposed ETS for buildings and road transport (a linear path to zero emissions in both sectors combined by about 2045). Our analysis shows that ethanol in internal combustion engine vehicles provides today the most cost-effective greenhouse gas abatement option, from a society point of view, that is if subsidies and taxation are excluded. It would be an attractive option to reduce emissions in the current fleet by increasing current ethanol mandates, and thus, new battery electric vehicles and ethanol can work complementary to reduce our fossil fuel dependency.

Other policy measures could further increase the demand for renewable ethanol. The Energy Taxation Directive could help to translate the attractive carbon abatement costs to an attractive pricing of ethanol fuel for the consumer. The Effort Sharing Regulation will force Member States to accelerate climate action in all sectors of the economy and as options in other sectors become exhausted, the focus will increasingly be on transport.

To increase the role of ethanol in climate action in the petrol passenger car segment requires both to increase the production of renewable ethanol within and above the cap and to facilitate the use of gradually higher blends in the existing fleet.

Recommendations for policy:

- Savings achieved by the introduction of electric vehicles are insufficient to reach 2030 climate targets, and therefore additional measures are needed for the fleet of internal combustion engine vehicles that remain in the market well beyond 2030.
- Higher ethanol blends in the passenger car segment can cost effectively reduce emissions of the passenger car market. It is recommended to have a E10 blending mandate across Europe and a gradual phasing in of E20.
- A retrofit programme for part of the legacy petrol car fleet can make these vehicles suitable for E85, at a low cost. This option could be especially relevant in countries and regions where the car fleet is typically replaced at a slow pace, and where consumers cannot (yet) afford electric vehicles (or subsidies are limited) and currently rely on the second-hand market.
- Carbon abatement in passenger cars requires higher production volumes of ethanol. This can be provided by both crop-based ethanol, which is currently capped under RED II, and by other renewable ethanol including advanced ethanol, produced from Annex IX A

feedstocks. Development of advanced ethanol requires innovation and scale, which are in turn dependent on investment certainty for the producing sector. Also, sustainable feedstock should be mobilised through targeted programs.[30]

Recommendations for the renewable ethanol producing sector

- The sector can influence to a great extent the future cost-effective position of high ethanol blends by sustainably increasing the production volumes. Enough supply of alternative fuel volumes in the market lead to cost-effective options for end-users.
- To supply ethanol above the caps that limit the contribution of food and feed crop-based ethanol and contribute to the necessary reductions in the current fleet, it is necessary to invest in the production of advanced ethanol. The sector should demonstrate the renewable ethanol industry's ability to produce from Annex IX A feedstocks and to contribute to the minimum Annex IX A targets set by the Renewable Energy Directive, and beyond.

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[30] Enough advanced biomass available for 50 to 100 Mtoe in EU in 2030 [Panoutsou & Maniatis (2021) - Sustainable biomass availability in the EU to 2050]. Potential advanced ethanol volume almost 70 billion liters in Europe in 2030 [E4Tech (2019) E20 Supply and Demand Study]

Appendix A Parameters used in the study

A.1 Vehicle parameters

Selection of vehicles

This study focuses on the greenhouse gas abatement costs of midsize passenger vehicles. Midsize segment, or B/C class vehicles, are deemed representative for cars driven by European consumers[31].The research should, if possible, be based on existing cars in the EU market, representing a fair share of the vehicles on the road. To enable a like-for-like comparison between the various powertrain-fuel combinations, the vehicles should be comparable in their function and market. We have therefore focused on sedan vehicles same as, or similar to, the Volkswagen Golf.

The Volkswagen Golf is the one of the most sold car models in the European Union in recent years.[32] Its electric counterpart, the Volkswagen ID.3, is also one of the most sold electric car models. Moreover, the Volkswagen offers the Golf model in different powertrain modes: a plug-in hybrid, mild-hybrid, biomethane, internal combustion engine running on petrol and diesel options, all of which are relevant for the current study.

To develop a representative crosscut of the EU market, we consider vehicles sold in three Member States: Germany, Italy and France. Out of 9.94 million new registered cars in Europe, 5.95 million of these registrations were in these three countries, representing around 60% of newly registered cars in Europe. Furthermore, the population share of the three countries equals to 49% of the whole European population.[33] The purchase costs in Table A1 below are taken as an average of purchase costs in these three countries.

The three countries provide multiple Volkswagen Golf models for specific fuel/powertrain combinations. The current study considers the most basic model price, excluding accessories and other add-ons. However, the three different countries offer different basic models to their consumers. In France and Italy, the models sold are more basic than in Germany. The models remained comparable, but Germany in general has a slightly lower fuel consumption.

If the desired powertrain/fuel combination of a Volkswagen Golf was not sold in one of the countries, we included a comparable car model (from a different brand) in terms of functionality, engine power and fuel consumption. For example, the CNG vehicle in France is based on a Seat Leon, which is also a mid-sized car with similar functionality, engine power and fuel consumption.

A car manufacturer may offer different cars per country, due to market preferences. For example, in France multiple manufacturers (including Volkswagen) offer flex-fuel vehicles, because of the E85 infrastructure in France, whereas in Italy and Germany, none of the brands offer flex-fuel vehicles. There may even be differences within a model sold in different countries. For instance, in January 2022, Volkswagen offered the ID.3 in Italy with a battery capacity of 45 kWh, whereas in France and Germany the smallest battery capacity for ID.3 was 58 kWh. Earlier research from studio Gear Up retrieved data for the purchase prices for 45 kWh Volkswagen ID.3 and this has been used for the purchase price of a small range BEV. This data was retrieved in May 2021 and could be slightly outdated.

Details on the vehicles chosen to represent the powertrains in the scope of the current study are given in the footnotes under Table A1.

Vehicle purchase price

For 2022 values, Table A1 shows the average purchase price of Volkswagen Golf or comparable brand/models in Italy, Germany and France. All data was retrieved in January

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[31] Internal analysis based on eight European countries done by studio Gear Up for FuelsEurope [studio Gear Up 2021, Low-carbon mobility with renewable fuels – affordability and accessibility of passenger cars for EU, report for FuelsEurope].

[32] Best selling cars website, 2020, 2019 (Full Year) Europe: Best-Selling Car Models.

[33] ACEA, 2021, Automobile Industry Pocket Guide 2021-2022

and February 2022. Only for the battery electric vehicle with a battery capacity of 45 kWh, the data was retrieved in May 2021. The purchase price including VAT was retrieved (mainly) from the Configurator on the Volkswagen website and recalculated to exclude the VAT in our model.

The flex-fuel vehicles purchase price is a calculated price. No flex-fuel vehicles are sold in Italy and Germany. Multiple OEMs offer flex-fuel vehicles in France, but there is no Volkswagen Golf variant. Ford offers flex-fuel vehicles with a similar functionality as the Volkswagen Golf, such as the Ford Focus and Ford Fiesta. But, Ford in general has lower purchase prices for their models (due to brand value and marketing). This would make the Ford Focus flex-fuel cheaper than the ICEV Volkswagen Golf, but the comparison would not be like-for-like. To make all powertrain-fuel combinations mutually comparable this study considers a ‘flex-fuel premium’ being the marginal difference in purchase prices between the petrol and flex-fuel version of the Ford Fiesta. This “flex-fuel premium” is then added on top of the price of the ICEV counterpart. So, for the mild hybrid petrol flex-fuel the premium was added to the mild hybrid purchase price (based on the Volkswagen Golf).

The flex-fuel premium calculated as described above is 1.200 €, This may be overestimating the additional costs of producing a flex-fuel vehicle. The additional production costs are probably around 300 €, however OEMs could ask more for the vehicles due to a smaller market[34].

No purchase price premium was added for diesel vehicles running on higher shares of renewable diesel, since we assume that the fuel is always of drop-in quality,[35] and no modifications to the vehicle are needed.

Table A1. Vehicle purchase costs ex VAT [Euro] in 2020

Drivetrain	Fuels	Costs (Euro)
ICEV Petrol	E5 / E10 / E20	22,313 1)
ICEV Petrol Flex-fuel	E85	23,513 2)
ICEV Diesel	B30 / B100	26,787 3)
Mild Hybrid Petrol	E5 / E10 / E20	25,203 4)
Mild Hybrid Petrol Flex-fuel	E85	26,403 5)
PHEV Petrol	E5 / E10 / E20	32,518 6)
PHEV Petrol Flex-fuel	E85	33,718 7)
BEV short-range 58 kWh	-	31,006 8)
BEV long-range 77 kWh	-	34,941 9)
CNG	Biomethane	25,293 10)

1) Based on Volkswagen Golf: Golf Life 1.0 TSI 6 CV 110 HP BVM 6 in France, a Golf 8 Life 1.0 TSI EVO 81 kW/ 110 CV manual in Italy, and a Golf Style 1,5 l TSI OPF 96 kW (130 PS) 6-speed in Germany. Data retrieved January 2022 from the VW Configurator.

2) Premium for flex-fuel calculated by the difference between a flex-fuel and ICEV (based on Ford Fiesta 1.0 Flex-fuel 95HP 6 rapports and Ford Fiesta 1.1 75HP 5 rapports in France). Car model is not sold in Germany and Italy. Data retrieved February 2022 from the Ford Configurator. Premium added to the ICEV petrol price.

3) Based on Volkswagen Golf: Golf Life 2.0 TDI 6 CV 115 HP BVM 6 in France, Golf 8 Life 2.0 TDI SCR 85 kW/ 115 CV in Italy and Golf Style 2,0 l TDI SCR 110 kW (150 PS) 7-Gang-Doppelkupplungsgetriebe DSG in Germany. Data retrieved January 2022 from the VW Configurator.

4) Based on Volkswagen Golf: Golf Life 1.0 eTSI 6 CV 110 HP DSG 7 in France, Golf 8 Life 1.0 eTSI EVO 81 kW/ 110 CV DSG in Italy and Golf Style 1,5 l eTSI OPF 96 kW (130 PS) 7-Gang-Doppelkupplungsgetriebe DSG in Germany. Data retrieved January 2022 from the VW Configurator.

5) Premium for flex-fuel calculated by the difference between a flex-fuel and ICEV. Data retrieved February 2022 from the Ford Configurator. Premium added to the MEV petrol price.

6) Based on Volkswagen Golf: Golf Style 1.4 eHybrid 8 CV 150 HP 204 CH DSG 6 in France, Golf 8 Style 1.4 TSI eHybrid 150 kW/ 204 CV DSG in Italy and Golf Style 1,4 l eHybrid OPF 110 kW (150 PS) / 80 kW (110 PS) 6-Gang-Doppelkupplungsgetriebe DSG in Germany. Data retrieved January 2022 from the VW Configurator.

7) Premium for flex-fuel calculated by the difference between a flex-fuel and ICEV. Data retrieved February 2022 from the Ford Configurator. Premium added to the PHEV petrol price.

8) In 2022, the top two car markets (DE,FR) only offer the 58 kWh option of the Volkswagen ID.3. The smaller 45 kWh option may either be discontinued or temporarily unavailable. Based on Volkswagen Golf: ID.3 Pro 107 kW 5 CV 145

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[34] Market insights from ePURE gathered through internal discussions

[35] The renewable diesel is assumed to consist of FAME or HVO or a (further undefined) mix of these.

HP in France, ID.3 Pro Performance Battery of 58kWh (net) 150 kW/ 204 CV in Italy and ID.3 Pro Performance 150 kW (204 PS) 58 kWh 1-Gang-Automatik in Germany. Data retrieved January 2022 from the VW Configurator.

9) Based on Volkswagen Golf: ID.3 Pro S 150 kW 5 CV 204 HP in France, ID.3 Pro S Battery of 77kWh (net) 150 kW/ 204 CV in Italy and ID.3 Pro S 150 kW (204 PS) 77 kWh 1-Gang-Automatik in Germany. Data retrieved January 2022 from the VW Configurator.

10) Italy and Germany are based on Volkswagen Golf: Golf 8 Life 1.5 TGI 96 kW/ 130 CV in Italy and 1.5 TGI 7-Gang-Doppelkupplungsgetriebe DSG in Germany. In France there was only a Volkswagen Polo driving on biomethane. A similar car to the Volkswagen Golf (type C, engine capacity and energy consumption) offered in Italy and Germany was the Seat Leon. Data retrieved for Leon NF 5D Style 1.5 TGI 130 HP (97kW) DSG7 in January 2022 from the French Seat website.

Depreciation

A vehicle loses value over time. At the end of an ownership period, the car is sold to a new owner. The difference between purchase price and resell value is depreciation. While some TCO models (e.g. ICCT[36]) incorporate the whole purchase price in their TCO model, the current study considers depreciation, to appreciate the remaining value of the car and to calculate the true costs over a certain ownership period.

In the current study, the total depreciation is calculated for 20 years and 250,000 km, and amounts 84%. The average per year is considered to calculate the costs in the first year.

On basis of the ANWB TCO calculator,[37] the depreciation rate depends on the number of kilometres driven (variable deprecation rate) and the ownership period in years (fixed depreciation rate).

The ANWB tool is based on data of cars in the Netherlands. An evaluation of TCO tools used in other Member States shows that the depreciation rate across Member States is comparable.[38][39]

Furthermore, this study has taken the same depreciation rate across all the included powertrain/fuel combinations. When testing this assumption by comparing the depreciation rate in online depreciation tools,[40] it is clear that the depreciation could differ between powertrains. Some models include a steeper depreciation rate for BEVs compared to ICEVs, related to fast technology advances and battery wear, while others include a more gradual depreciation rate for BEVs, based on the lower mechanical complexity. We conclude that the depreciation rate for BEVs is uncertain due to their limited and recent entrance into the passenger car market. We assume that any potential differences between ICEVs and BEVs will further decrease, and thus, the TCO model assumes a value loss for BEVs similar to ICEVs. This assumption can only be further verified once more data on electric vehicles becomes available.

For the flex-fuel vehicles there is no strong evidence that their depreciation rate would differ from ICEVs. Autoweek and other studies show similar depreciation rate for flex-fuel vehicles.[41] However, resell value could be influenced as there might be a smaller demand for second hand flex-fuel vehicles.

Vehicle energy consumption

The energy consumption of C-segment (midsize) passenger cars was retrieved from the same references as their respective purchase costs. France and Italy were found to have in general higher fuel consumptions. This may indicate that Volkswagen sells its newest models to the German market first and the data found for Italy and France belong to models from the previous year. This could explain the difference in energy consumptions. This study has

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[36] Using vehicle taxation policy to lower transport emissions: An overview for passenger cars in Europe" (2018) study by the International Council on Clean Transportation (ICCT)

[37] The Dutch motoring club ANWB offers a TCO calculator that provides a great level of detail and transparency, and allows for adapting assumptions for cost calculation (ANWB Autokosten).Therefore, it has been replicated/"reverse engineered" also by other parties, such as the International Council on Clean Transportation (ICCT) in their 2018 study "Using vehicle taxation policy to lower transport emissions: An overview for passenger cars in Europe".

[38] The money calculator, 2021, Car depreciation by make and model.

[39] Omnicalculator, 2021, Car depreciation calculator.

[40] Autoweek, 2021, Kostenberekening auto.

[41] CarEdge, 2019, Ford Flex depreciation

taken an average of the three countries to represent an average fuel consumption of the vehicles.

The consumption is generally reported by OEMs in litres petrol, litres diesel, kilowatt-hours electricity or kilogrammes natural gas per 100 kilometres. This information was converted into megajoules per 100 kilometres (in the case of fuels, the lower heating values were taken), which allowed for calculating the specific consumption of the assessed fuel blends.

We assume the thermal efficiency of the internal combustion engine remains constant from pure petrol to E20 blends and from pure diesel to B100 blends. Nevertheless, it should be noted that the B100 blend was assumed to contain 10 vol.% FAME and 90 vol.% HVO, therefore resulting in a highly paraffinic blend that lacks aromatics. Furthermore, such blend has a lower density and different lubricity properties compared to conventional diesel. A non-calibrated engine may therefore exhibit higher real-life fuel consumption than presented in this study.

For E85 blends, the reported efficiency of a flex-fuel vehicle was used, although differences between reported and calculated E85 consumption values were minor. The slight differences may be explained by rounding in reported values. Hybrids running on a high ethanol in petrol blend are currently not sold in the European Union. It was assumed that they consume the same amount of energy (in megajoules per 100 kilometres) as petrol hybrid vehicles.

Table A2 shows the energy consumptions for the powertrain/fuel combinations.

Table A2. Vehicle fuel economy. [1]

Drivetrain and fuel	Fuels	Consumption
ICEV Petrol	E5 / E10 / E20	5.4 litre petrol equivalent/100 km (2) (169.8 MJ/100 km)
ICEV Petrol Flex-fuel	E85	7.2 litre/100 km (165.0 MJ/100 km)
ICEV Diesel	B30 / B100	4.1 litre diesel equivalent/ 100 km [2] (147.4 MJ/100 km)
Mild Hybrid Petrol	E5 / E10 / E20	5.05 litre petrol equivalent/100 km [2] (161.8 MJ/100 km)
Mild Hybrid Petrol Flex-fuel	E85	7.1 litre/100 km (162.7 MJ/100 km)
PHEV Petrol	E5 / E10 / E20	0.91 litre petrol equivalent/ 100 km [2] and 14.01 kWh/ 100 km (79.5 MJ/100 km)
PHEV Petrol Flex-fuel	E85	1.27 litre/100 km and 14.01 kWh/ 100 km (79.5 MJ/100 km) [3]
BEV short-range (58 kWh)	-	15.6 kWh/100 km (56.2 MJ/100 km)
BEV long-range (77 kWh)	-	15.8 kWh/100 km (56.9 MJ/100 km)
ICEV CNG	Biomethane	3.63 kg/100 km (171.1 MJ/100 km)

1) Consumption data was retrieved from the same sources as the corresponding vehicle purchase costs. All consumption data was averaged over the three countries. The maximum observed deviation between countries was ± 0.2 L/100 km (see Table A1 above for source data references).

2) Consumption in litres depends on the fuel blend. The higher the blend of renewables, the more litres are consumed. Consumption in megajoules is assumed constant per powertrain, irrespective of the blend (apart from the high-octane E85 blends).

3) For lack of availability, the combustion engine efficiency of the flex-fuel PHEV was assumed to equal the combustion engine efficiency of the regular PHEV. Higher consumption results from the lower heating value of E85 compared to pure petrol.

Other assumptions related to the vehicle

Mileage and lifetime of vehicles

The general expected total mileage of a vehicle over a lifetime is between 200,000 and 300,000 kilometres. In the current study, we assume that the vehicle is used by a private driver, with a 12,500 kilometres annual mileage. Note that annual mileage in Europe is decreasing and was in 2019 around 11,500 kilometres per passenger vehicle.[42] We furthermore assume a lifetime of 20 years, thus resulting in the total lifetime mileage of 250,000 kilometres. Business drivers would typically have a higher annual mileage, likely resulting in a shorter vehicle lifetime in terms of years.

Maintenance

The maintenance costs of ICEVs are well known. There is some uncertainty about the maintenance costs of BEVs. Some TCO models assume lower maintenance costs for BEVs due to having fewer moving parts than an ICEV. However, other TCO models assume higher maintenance costs, as spare parts of BEVs are more expensive and repairs may take longer.

In the current study, the maintenance costs of ICEVs, ICEV flex-fuel vehicles and BEVs are based on the ANWB model[43]. Judging from literature, more experience with BEVs would be necessary to increase certainty on BEV maintenance costs.

Maintenance costs are expressed by a formula including fixed and variable costs. The annual maintenance costs for midsize passenger cars consist of a fixed and a variable component as given in Table A3.

Table A3. Fixed and variable maintenance costs [studio Gear Up 2021, Affordability of battery-electric vehicles in the EU]. As an example, an ICEV driving 12,500 km per year would have a total maintenance cost of 143 + 12.2 x 12.5 = 296 Euro.

Table A3. Fixed and variable annual maintenance costs in 2020.

Drivetrain	Fixed maintenance (€ / year)	Variable maintenance costs (€ / 1000 km / year)
ICEV (1)	220	19.0
BEV (1)	118	10.1
PHEV and HEV (2)	169	14.6

(1) Based on formula's derived from the 2021 study by studio Gear Up for FuelsEurope [studio Gear Up 2021, Affordability of battery-electric vehicles in the EU], especially Figures 16 and 17. For the current study, taxes (21%) are excluded and therefore extracted from the FuelsEurope values.

(2) Maintenance costs for the plug in and mild hybrids are taken as an average between ICEV and BEV as explained in the text.

The regular and flex-fuel ICEVs have the same maintenance function. For the hybrid models (mild hybrid and plug-in hybrid) the maintenance costs are between those of ICEVs and BEVs. As the hybrids have less moving parts than ICEVs, the maintenance costs are lower, but still having an internal combustion engine the hybrid has higher maintenance than the BEV. We assume the maintenance cost of hybrid vehicles will be halfway between that of ICEVs and BEVs.

Insurance

Insurance costs differ greatly between regions, car brands and consumer profiles. We assume a fixed percentage of 2.93% of the catalogue price for all cars in the current study, which is altered to show an annual insurance cost. This agrees with the different online TCO Models (ANWB, Autoweek and ADAC).[44]

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[42] Odyssee-Mure, n.d., Change in Distance Travelled by Car

[43] ANWB autokosten berekenen tool. Publicly available on their website. Analysis done by studio Gear Up.

[44] ADAC 2021, ADAC Autokosten-Rechner.

Electric driving share

The electric driving share can significantly impact the costs of a plug-in hybrid. In general, household electricity costs are lower than fuel costs. If the PHEV drives a higher share on fuel rather than electricity the costs will increase. The Worlwide Harmonised Light Vehicle Test procedure (WLTP) leads to an electric driving share up to 86%, but there is a high variation in the utility factor (the proportion of distance travelled in electric mode[45]) of electric vehicles between consumers. A study of the Fraunhofer Institute found the WLTP overestimating the utility factor for plug-in hybrid. For the study results an electric driving share of 75% is assumed, which is on the higher site of the results of the Fraunhofer Institute.

Private/public-charging ratio

The private/public-charging ratio is a main driver of the energy costs of a plug-in hybrid and battery electric vehicles. The ability of electric vehicle drivers to charge public or private is partly dependent on their living situation and driving profile. For example, a car owner living in a city centre could have limited availability to charge private. Or, a car owner driving more kilometres will fast charge more often. As, not every Member State has the ability to fast charge and an average consumer (not a business driver) is assumed for the current study, we exclude fast charging. For the private/public charging ratio we assume the same 50/50% ratio for plug-in hybrids as BEVs to average out spatial and driver type differences.

Influence of import taxes

In the calculation of greenhouse gas abatement costs, this study excludes taxes and subsidies where possible. The purchase price of vehicles in the EU is impacted by important taxes (e.g. for steel and batteries, and for vehicles imported to the EU). The impact of these import taxes could not be excluded from the current study.

A.2 Energy costs

Fuel prices for consumers include significant taxes in the form of excise duties and value added tax (VAT). These are excluded from the current analysis.

The typically large fluctuations in fuel prices over time were addressed by averaging fuel costs from January 2019 to January 2021. The Weekly Oil Bulletin by the European Commission provides this cost data for pure Super-95 unleaded petrol and for diesel oil, with a weighted average of EU-27. The (commodity) prices of ethanol and fatty acid methyl ethers (FAME) were retrieved from F.O. Licht for the same period. The ethanol price was based on prices delivered through contracts in North Europe. The FAME price was based on a fob ARA region price. Household electricity prices (before taxes) were retrieved from Eurostat for the same period. The commodity price of hydrotreated vegetable oils (HVO) was retrieved from S&P Global Platts (representing the price of HVO in North-western Europe). Public charging prices were retrieved from a previous studio Gear Up assessment for FuelsEurope.

The costs of blends (excl. taxes) were assumed to follow a linear trend between the costs of all blending components. The costs of blending or increased logistics were thus assumed to be negligible. For blends of ethanol in petrol and biodiesel in diesel, we have assumed the blends to exactly contain the volume fraction of biofuels that is suggested by the number in the blend specification. So, E85 contains exactly 85 volume % of ethanol. The real volumetric percentages of the blends at the fuel stations are typically lower (E85 typically contains 60-75 volume % of ethanol).

The biodiesel blends are assumed to contain FAME and/or HVO. So, B30 contains a certain amount of HVO and FAME to arrive at 30% biodiesel by volume. Note that blends above 30 volume % HVO do not comply with the density requirements of the EN590 norm[46]. Several European Member States, however, still allow HVO100 to be sold at service stations under the EN15940 norm. Also, E20 does not currently comply with the petrol standard E228, but the

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[45] Fraunhofer Institute (2021) Realistic Test Cycle Utility Factors for Plug-in Hybrid Electric Vehicles in Europe

[46] Website Den Hartog: CO_2 savings biodiesel – Hydrotreated Vegetable Oil (HVO). Retrieved on 17 March 2022

option is considered in policy discussions and CEN is drafting a potential E20 norm.[47] Adaptations are minor even for the existing fleet.

The fuel and energy costs listed in Table A4 include the infrastructure costs of different types of energy. However, for ethanol, FAME and HVO, the study includes commodity prices (which excludes infrastructure costs). But, the influence of infrastructure costs should be very low for these fuels, especially when calculated per vehicle (and assuming sufficient occupancy of the fuel pumps). For bio-CNG the infrastructure costs are included, as the pump prices minus the taxes were taken.

For electricity the infrastructure costs are partly excluded in the concept results. Public charging prices do not fully include the infrastructure cost, as charging infrastructure is often subsidised. But, Eurostat electricity prices include the costs of grid operation, maintenance costs et cetera. For private charging, it does not include the investment for the charging unit a customer has to buy.

Table A4. Cost of fuels (excluding VAT and excise) expressed in the typical sales unit (per litre, per kg, per kWh) and, for mutual comparison, expressed per energy unit. All percentages are expressed in volume percent.

Energy carrier	Average costs Jan 2019 – Jan 2021	
Pure petrol 95 unleaded	0.503 €/l 1)	15.71 €/GJ
Pure diesel	0.542 €/l 1)	15.06 €/GJ
Ethanol (anhydrous)	0.603 €/l 2)	28.31 €/GJ
Fatty acid methyl ethers (FAME)	0.754 €/l 2)	22.33 €/GJ
Hydrotreated vegetable oil (HVO)	0.960 €/l 3)	28.65 €/GJ
Petrol E5 (5 % ethanol)	0.508 €/l 4)	16.14 €/GJ
Petrol E10 (10 % ethanol)	0.513 €/l 4)	16.58 €/GJ
Petrol E20 (20 % ethanol)	0.523 €/l 4)	17.51 €/GJ
Petrol E85 (85 % ethanol)	0.588 €/l 4)	25.67 €/GJ
Diesel B30 (10 % FAME, 20 % HVO)	0.647 €/l 4)	18.34 €/GJ
Diesel B100 (10 % FAME, 90 % HVO)	0.939 €/l 4)	28.01 €/GJ
Compressed biomethane	1.29 €/kg 5)	27.39 €/GJ
Household grid electricity	0.128 €/kWh 6)	35.53 €/GJ
Public-charging grid electricity	0.286 €/kWh 7)	79.44 €/GJ

1) European Commission – Weekly Oil Bulletin History (retrieved January 2022) provides weighted European prices, excluding taxes. A non-weighted average of all price data between January 2019 and January 2021 was taken.
2) Contractual and delivered prices retrieved from F.O. Licht commodity prices for North Europe. Prices were averaged between January 2019 and January 2021.
3) Prices retrieved from website of S&P Global Platts in February 2022, representing North-Western Europe.
4) All blends are calculated assuming a linear interpolation between the blending components' prices listed above.
5) OrangeGas provided Dutch material prices for bio-CNG excluding VAT and excise duties. Retrieved on the website of OrangeGas, February 2022.
6) EU-27 average for medium sized households between beginning 2019 and end 2020. Data was retrieved from Eurostat [NRG_PC_204, NRG_PC_205] in February 2022.
7) In the studio Gear Up report on the total cost of ownership of passenger cars for FuelsEurope, it was found that on average, public charging is offered at a 0.20 €/kWh premium (including taxes) compared to household charging. That analysis included price data for 16 European Member States. It was assumed that the (absolute) taxation is equal for household electricity and public-charging electricity (around 0.09 €/kWh).

A.3 Fuel greenhouse gas impacts

To assess the greenhouse gas abatement costs of various energy carriers the lifecycle emissions were taken into account. Lifecycle emissions include the emissions of producing the fuel or generating the electricity and operating the vehicle. Often called Well-to-Wheel emissions. For the greenhouse gas emission intensity of ethanol an average was taken between the reported greenhouse gas emissions of ethanol in the Netherlands (by the Dutch

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[47] Horizon Magazine – Why raising the alcohol content of Europe's fuels could reduce carbon emissions https://ec.europa.eu/research-and-innovation/en/horizon-magazine/why-raising-alcohol-content-europes-fuels-could-reduce-carbon-emissions. Retrieved on March 21, 2022

Emission Authority (NEa)), Germany (by the Federal Office for Agriculture and Food) and ePURE. For biodiesel an average was also taken with the Dutch and German greenhouse gas intensities and a value given by EBB (European Biodiesel Board). For biomethane a wide range of greenhouse gas intensities (positive and negative) can be applicable dependent on the feedstocks. In this study an average was taken between different types of feedstock (e.g. manure, energy crops, wastewater sludge and sileage maize). As manure and wastewater sludge have a limited availability, so it would be more likely to have a mix of feedstocks to produce biomethane.[48] For the greenhouse gas intensity of grid electricity, the EEA reported EU-27 average in 2020 was taken[49]. The EEA assumes zero greenhouse gas intensity for renewable electricity; however this study has incorporated a greenhouse gas intensity for renewable electricity. By using the greenhouse gas intensities given for solar, wind, biomass and hydropower generated electricity and combine them with their respected shares in the European electricity generation.[50]

Furthermore, the cradle-to-grave emissions were included for the plug-in hybrids and the electric vehicles. For the mild hybrids no cradle-to-grave emissions were included, as these batteries are around 0.5 kWh, and thus, their associated emissions are negligible. The cradle-to-gate emissions of the vehicle production of an ICEV (including the engine) is roughly the same as the production of a battery electric vehicle production (excluding the battery). For medium sized cars the production of an electric vehicle (excluding the battery) is even slightly higher, but for bigger cars the ICEV production emissions are higher than a battery electric vehicle (excluding the battery).[51]

Emissions of petrol and diesel may rise in the future, due to risk of scarcity and the transition towards complex oil sources and stricter sulphur requirements.[52] Some use of renewable hydrogen could however also potentially bring it down. For ethanol and renewable diesel improvements in greenhouse gas intensity are expected due to a change in feedstocks (more waste based and therefore less upstream impacts), improved feedstock production and conversion technologies (less fertilizer application, higher yields, use of renewable energy in conversion facilities). Improvements are driven by legislation, proposed renewable energy directive is stimulating better performing greenhouse gas intensities.[53]

The disposal process has the same greenhouse gas impact of around 6% of the manufacturing process. Thus, this study has taken an assumption of 6.7% of the manufacturing process equals the greenhouse gas impact of the disposal (the same assumption was done for the greenhouse gas intensity of the disposal process in 2030, even though the Fraunhofer study showed an increase share of the impact of the disposal process). In 2030, the manufacturing emissions of batteries are expected to decrease due to a shift to European production.[54]

Table A5 shows the lifecycle greenhouse gas emissions for the various energy carriers.

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[48] Zhou, Swidler, Searle & Baldino (2021), Life-Cycle Greenhouse Gas Emissions of Biomethane and Hydrogen Pathways in the European Union

[49] European Environment Agency (EEA) website. Greenhouse gas emission intensity of electricity generation by country in 2020. Retrieved in January 2022.

[50] Median lifecycle carbon intensity of wind, solar PV [Nugent and Sovacool 2014, Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey], hydropower [IHA 2018 Hydropower status report] and biopower [Xu 2021, Regionalized Life Cycle Greenhouse Gas Emissions of Forest Biomass Use for Electricity Generation in the United States].

[51] EEA (2018). Electric vehicles from life cycle and circular economy perspectives TERM 2018: Transport and Environment Reporting Mechanism (TERM) report

[52] As seen for instance in Oil-Climate-Index by Carnegie Endowment (accessed March 21, 2022).

[53] Newly proposed version of Directive 2018/2001 by the European Commission. Published in July 2021, still under debate.

[54] Fraunhofer Institute Greenhouse for Solar Energy Systems ISE (2019). Gas Emissions for Battery Electric and Fuel cell electric vehicles with ranges over 300 kilometres]. Base-case 2030.

Table A5. Fuel and energy greenhouse gas impacts [g CO_2eq/MJ or g CO_2eq/kWh as indicated].

Energy carrier	Well-to-wheel greenhouse gas emissions
Petrol	94 g/MJ 1)
Diesel	94 g/MJ 1)
Ethanol	19.3 g/MJ 2)
Biodiesel	19.5 g/MJ 3)
Biomethane	0 g/MJ 4)
Grid electricity	230.7 g/kWh 5)
Renewable electricity 6)	12.5 g/kWh 7)
Battery impact	Manufacturing: 124 kg CO_2eq/kWh 8) Disposal: 8 kg CO_2eq/kWh 8)

1) The official comparators for petrol and diesel in the EU [Directive EU 2015/652] have been assumed to be still valid.

2) Average of 2019 values reported by the German regulator BLE, the Dutch regulator NEa and EU producers' association ePURE [studio Gear Up 2021, Greenhouse gas savings from biofuels in Germany].

3) Average of 2019 values reported by the German regulator BLE, the Dutch regulator NEa [studio Gear Up 2021, Greenhouse gas savings from biofuels in Germany] and EU producers' association EBB [personal correspondence Hamelinck with EBB].

4) Average taken between different types of feedstock (e.g. manure, energy crops, wastewater sludge and sileage maize). As manure and wastewater sludge have a limited availability, so it would be more likely to have a mix of feedstocks to produce biomethane. greenhouse gas intensities of different feedstocks were taken from a study of ICCT [Zhou, Swidler, Searle & Baldino 2021, Life-Cycle Greenhouse Gas Emissions of Biomethane and Hydrogen Pathways in the European Union].

5) European average of the carbon footprint grid electricity in 2020 [EEA, GHG emission intensity of electricity generation by country]. Note this assumes renewable electricity has zero emissions, contrary to the specific factor for renewable electricity in the next row cf. footnotes 10-13.

6) The operational phase of renewable electricity induces some emissions: from decomposing biological material in hydropower installations, from maintenance and lubricant use in wind turbines, and from cleaning of solar PV panels. Note that the emissions from manufacturing solar panels and wind turbines or during the construction of power stations can generally be ignored and are not included.

7) Median lifecycle carbon intensity of wind, solar PV [Nugent and Sovacool 2014, Assessing the lifecycle greenhouse gas emissions from solar PV and wind energy: A critical meta-survey], hydropower [IHA 2018 Hydropower status report] and biopower [Xu 2021, Regionalized Life Cycle Greenhouse Gas Emissions of Forest Biomass Use for Electricity Generation in the United States] have been combined with their respective shares in the EU market [Eurostat 2022, Renewable energy statistics]. Wind 36%, Hydropower 33%, Solar 14%, Solid biofuels 8%.

8) Fraunhofer Institute ISE[41] researched three battery production and end-of-life scenarios (best case, base case, worst case). This study has taken the greenhouse gas impact from the base case. Significant share of the impact comes from the electricity used during the manufacturing process. The base case calculates the greenhouse gas impact taken the 2020 grid average of the main battery-manufacturing countries.

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