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Pathways to Decarbonise the European Car Fleet: A Scenario Analysis Using the Backcasting Approach

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Abstract: This paper analyses decarbonisation scenarios for the European passenger car fleet in 2050. The scenarios have been developed using the backcasting approach and aim to reduce greenhouse gas (GHG) emissions of passenger cars to a level defined in the Transport White paper that is 60% below 1990 levels. Considering the emission levels of 2010, a yearly reduction of 1.7% is required in order to achieve the target. Car emissions were decomposed into the main emission factors of mobility, efficiency and carbon intensity. How these factors change over time depends on various external factors: the pace of technological improvements, the future role of cars in society's mobility system and the priority given to decarbonising energy demand. The analysis showed that if car mobility and ownership continue to increase as expected in a 'business as usual' case, a share of 97% plug-in hybrid or battery electric vehicles might be required by 2050, together with a substantial decrease in greenhouse gas emission from electricity production. A transition to more advanced car technology such as automated driving, advanced batteries or lightweight materials in vehicle production would raise vehicle efficiency. Should car mobility continue at a high level, an early technology transition will be required.

Keywords: energy efficiency; electric and hybrid vehicles; CO₂ emissions; environmental effects

1. Introduction

Decarbonising transportation is a major task of European transport policy-making. A successful decarbonisation strategy will have to promptly address several key issues linked to car mobility and efficient vehicle technology. Increasing the environmental sustainability is taken very seriously, since it assures the long-term survival of society [1]. An indicator for imbalances in our ecosystem is the constant increase in average global temperature. Limiting the temperature increase to two degrees Celsius by 2100 compared to pre-industrial times is seen as a threshold which should not be crossed. Severe climate changes could otherwise result, leading eventually to high societal costs [2]. At the Paris Climate Conference in 2015, the European Union (EU) member states and other countries committed to constantly monitoring the progress in reducing carbon emissions [3]. Human activity such as transport, energy production or heating leads to greenhouse gases such as carbon-dioxide (CO₂) and is accelerating the temperature increase. GHG emissions have been curbed in most sectors during past decades, a noticeable exception being the transport sector. The European Commission (EC) has responded by issuing a target of a reduction of 60% in transport emissions by 2050, compared to 1990 levels [4]. Furthermore, the Commission's objective is to curb GHG emissions from all sectors in Europe by 80% [5]. Binding legislations for member states which are considered to be necessary steps to reach the 2050 emission target have been issued. These include, for instance, the regulation of

emission levels for newly registered vehicles [6] and the directive on mandatory shares of renewable energy sources [7].

The European car fleet is responsible for 12% of European GHG emissions and is the subsector that contributes most to transport emissions. High dependency on fossil fuels makes it a challenge for the passenger car fleet to meet the EC emission target. Nearly 99% of the European Union's (EU-27) car fleet consists of diesel and gasoline cars. Furthermore, the share of passenger-kilometres driven by car is 73% or 4700 billion in the EU-27, which stresses the importance of focusing decarbonisation efforts on car use. But also, light and heavy-duty vehicles play a crucial role for decarbonisation in the freight transport sector. The relative contribution of heavy duty vehicles to GHG emissions per ton-kilometre is even higher than for passenger cars, in relation to passenger-kilometres [8]. Reference scenarios for the EU-27 transport system predict a constant increase in car use until 2050 [8,9]. A review of decarbonisation scenarios in different regions showed that car use is considered the strongest driving force behind car emissions, which applies particularly to developing countries with increasing car ownership [10]. This paper aims to: (1) contribute to a better understanding of what must be done to decarbonise the European car fleet to the desired level and (2) to develop alternative scenarios for a more environmentally sustainable car fleet in 2050. These scenarios are compared to a 'business as usual' (BAU) case which describes the continuation of current trends.

A previous literature review proposes two approaches for analysing decarbonisation scenarios [10]. The forecasting approach uses transport and emissions models to answer the question 'what happens if changes of a certain magnitude are applied to the situation today'. The backcasting approach is applied where a target is specified as ex ante in relation to a sustainability problem. The central question answered with backcasting is 'what must happen to reach the desired sustainable future'. Backcasting is the suitable method when the required changes leading to the desired future need to be quantified (first objective in this paper) and pathways towards this future should be defined (second objective). The assumptions underlying these pathways may need to be progressive when using backcasting, especially if the objective itself is ambitious. The assumptions here may seem unfeasible at first and they ultimately require validation by experts. In backcasting, several images or scenarios are designed, representing futures where societal problems have been solved [11]. The approach is popular among those analysing alternatives for decarbonising the transportation sector [11–13]. These alternative scenarios are based on assumptions made while there is still uncertainty about the many long-term trends which will occur. Scenarios developed with backcasting can help understand the magnitude of the changes to these trends that are required in order to achieve the target. In its commonly-used form, the backcasting approach consists of three main steps: (1) first, the problem and an objective are defined, (2) then several future images or scenarios are outlined in such a way that this specific target is met and (3) the paths that lead to these scenarios are analysed and compared to a 'business as usual' case.

2. Emission Target

The increased demand for driving has raised concerns about the long-term environmental impacts. On the other hand, stricter legislation such as the emission performance standards for new passenger cars [6] has led to a constant decrease in car emissions [14]. Also, low-CO₂ alternatives to oil will become indispensable to decarbonise transportation [15] which means that the passenger car fleet has to be shifted towards alternative fueled cars. Increasing their share will reduce the dependency on fossil fuels and reduce the amount of exhaust emissions. A number of initiatives linked to decarbonisation were proposed in the White Paper which eventually should lead to the 2050 emission target and help reducing the transport emissions. In a recent report the Commission admits that while sufficient measures to tackle the problem have been proposed, the adoption of these proposals and their implementation is lacking behind [16]. This stresses the need for swift measures to avoid any delays in implementing measures until 2050.

The objective in this paper is to define such pathways that will reach the emission level indicated in the White Paper. The White Paper target target initially considers the transport sector as a whole and

names the objective as the reduction of its emissions by 60% up till 2050. For the purposes of this study, we assigned this target to the EU-27 passenger car fleet. The reduction is compared to the emission level in 1990. As 95% to 99% of all GHG emissions resulting from car use are CO₂ emissions [17], the most commonly-used unit is the amount of CO₂, e.g., in megatons (Mt CO₂). The first row of Table 1 shows the emission levels for Europe and the second row shows those of the European transport sector. The information was obtained from the annual Transport in Figures report, published by the European Commission [18]. The third row shows a desired level of emissions for passenger cars, and is an estimate based on emissions levels indicated in the EU-27 transport sector scenario, developed by the ‘EU Transport GHG: Routes to 2050’-project [19] and the information provided in the 2011 White Paper for the European Transport Sector [4].

Table 1. Emission targets using 1990 and 2010 values. Source: [18,19].

	Year	1990	2010	2050 Target (−60%)	Yearly Reduction 1990–2050	Yearly Reduction 2010–2050
1	All sectors GHG (Mt CO ₂)	5583	4721	2233	−1%	−1.32%
2	Transport sector GHG (Mt CO ₂)	959	1216	384	−1%	−1.71%
3	Passenger cars (Mt CO ₂)	575	777	230	−1%	−1.76%

The threshold value for the EU-27 car fleet is a maximum of 230 megatons CO₂ in 2050. Reaching this level requires a yearly average reduction of 1.76% on 2010 levels. The reduction rate is ambiguous, considering current trends of car use. The total amount of vehicle-kilometres travelled (VKT) is increasing at a rate of 1.9% per year [20] and the average consumption of conventional passenger cars decreases yearly by 0.4% to 3% [21]. The uncertainty about future trends makes it difficult to estimate how these diverting factors of car emissions will develop in the future. VKT growth may slow down and a ‘peak travel’ [22] could be reached before 2050. On the other hand, the technological potential to further increase the efficiency of conventional cars is limited, so that yearly efficiency gains could become smaller than they have been so far. Further efficiency gains are however still possible by reducing the average fleet weight, for instance if smaller cars are chosen or if lightweight materials are used in vehicle production. Given the current car fleet, a low rate of decrease in fuel consumption would mean that the additional car use is driving emissions, and the gap to the target level widens. Table 1 shows that the gap is smaller when looking at the combined emissions levels of all sectors. This indicates just how far the passenger car fleet is lagging behind in terms of achieving the White Paper targets. However, uncertainties about these predictions remain.

3. Decomposition Approach

Information about the development of car emissions is usually retrieved from emission models. The choice of a model and its output depends on the purpose of the study. The Passenger Car and Heavy Duty Emission Model (PHEM) calculates car emissions for individual driving cycles and environments and the Handbook of Emission Factors for Road Traffic (HBEFA) provides aggregated car emissions by different vehicle classes. In the present case it was of interest to receive information about the European car fleet on an aggregated level. The data for this purpose was retrieved from EU-27 transport scenarios [19] using TREMOVE model data. TREMOVE is a policy assessment model to study the effects of different transport and environment policies on the emissions of the transport sector [23] and a common source for vehicle based emission data on European level. The information from TREMOVE was integrated in a spreadsheet model which helped estimating the emission level in the decarbonisation scenarios. The model assisted in developing scenarios which would reach the desired emission target of 230 Mt CO₂ by 2050. For this purpose, car emissions were decomposed into single emission factors. The decomposition of car emissions is a common approach to better understand the driving forces behind them [24–26]. Different emission factors and methods to quantify emission levels are used in the decomposition literature, depending on the scale

of the analysis. The decomposition methodology applied here follows the so called Kaya identity [27]. The Kaya identity is used to analyse the influence of demand, technology and population changes on the environment. McCollum and Yang [25] applied this method to evaluate U.S. transport emissions in different sectors and Kwon [28] analysed CO₂ emissions from car use in Great Britain. The spreadsheet model considers four different emission factors and six influencing factors which are shown in Figure 1. The influencing factors were adjusted in a way so that the desired emission level for the European car fleet is reached. Adjustments were made in percentage changes to the values for the baseline case, described further in the next section. This way it was assured that the targeted emission level will be reached by the respective adjustments.

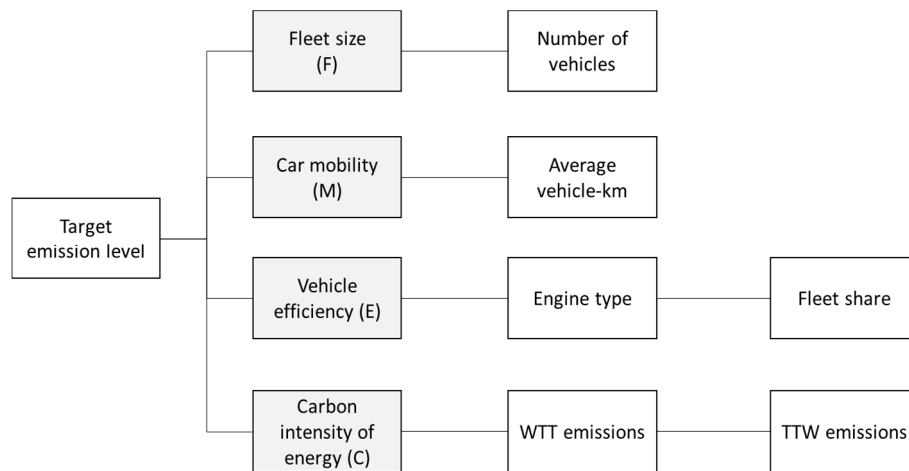


Figure 1. Factors in spreadsheet model to develop decarbonisation scenarios. Note: emission factors in grey boxes, data used to estimate these factors in white boxes. Source: authors' own illustration.

The factor car fleet size (F) is the number of cars included in the EU-27 fleet in a certain year, car mobility (M) is the average distance driven by car (km per vehicle). These factors relate to car use. The efficiency factor (E) is the average energy consumption per kilometre travelled, in kilowatt-hours (kWh per km). The carbon intensity factor (C) is the amount of well-to-wheel emissions (WTT) emitted by one unit of energy (CO₂ per kWh). Emissions resulting from the production and distribution of energy are called well-to-tank emissions (WTT). Tank-to-wheel emissions (TTW) are emitted as exhausts when driving the car. Final car fleet emissions were calculated as shown in Equation (1):

$$\text{CO}_2 = \text{Fleet size} \times \left(\frac{\text{Travel}}{\text{Car}} \right) \times \left(\frac{\text{Energy}}{\text{Travel}} \right) \times \left(\frac{\text{CO}_2}{\text{Energy}} \right) \equiv F \times M \times E \times C \quad (1)$$

the factors (F) and (M), as well as (E) and (C), were combined for the calculation of the emissions. The number of cars in the fleet (F) is simply multiplied by the average vehicle mileage to obtain the vehicle-kilometres travelled. To combine (F) and (E), the fleet share s_i of engine type i is multiplied by the respective vehicle efficiency e_i and carbon intensity of energy type j , as shown in Equation (2). The sum is the average carbon intensity of car use in the EU-27 fleet:

$$E \times C = \sum_{i,j} s_i \times e_i \times c_j \quad (2)$$

in a subsequent step, the data for the factors (F), (M), (E) and (C) was collected from different sources to develop a 'business as usual' case.

4. Baseline

4.1. The Baseline Year 2010

To quantify the reduction in emissions needed, a reference case had to be established. The reference case describes the path from today until 2050 if no further actions are taken. The information on how to quantify the emission factors and the respective data sources are listed in detail in Appendix A. The data on car use includes the average annual mileage of vehicles and the number of cars in the vehicle fleet. The information was obtained from various household surveys and as survey data is not available on a European level, the average mileage was estimated using national survey data from the United Kingdom [29], Germany [30], the Netherlands [31] and reported mileages in vehicle statistics [32] and an EU-27 ‘business as usual’ scenario [19]. The average of reported EU-27 vehicle fleet size in vehicle statistics [14,20,33] and scenarios [8,20,23] was considered for the base year 2010. The ‘business as usual’ scenario, developed within the research project EU Transport GHG: Routes to 2050 [19], included a good overview of vehicle efficiencies for common engine types and the respective shares in the EU-27 vehicle fleet. The efficiency rates of cars were compared with other sources, for conventional car [34] as well as electric vehicle (EV) efficiencies [35]. The SULTAN scenario was shown to be on the higher end of the reference sources, which was considered sufficiently accurate, also because real world emissions have shown to be somewhat higher than numbers published by manufacturers [21]. A good overview of WTW emissions of different energy types is provided in the European Commission report Well-to-Wheels analysis of future automotive fuels and powertrains in the European context [36]. The categorisation of direct and indirect emissions and the summary of primary energy sources in the European electricity mix was especially useful. This made it possible to quantify and integrate the impact of higher renewable energy shares on the decarbonisation of car use into the approach.

4.2. The Reference Year 2050

For the reference case, it was necessary to identify relevant ‘business as usual’ trends concerning the emission factors. The SULTAN scenario was the main data source here because it includes trends in 2050 for most of the emission factors. The data was compared to other sources where possible, the detailed overview of the 2050 data is given in Appendix A. The change in vehicle fleet size accounts for 30% more vehicles and the average mileage for 2% more vehicle use in 2050. The average efficiency increase of vehicles in the SULTAN scenario was compared to two other studies. The average yearly efficiency increase in conventional cars is between 1.03% to 1.23% which is similar to numbers found in [37,38]. EV efficiency increases by 0.86% for battery electric vehicles (BEV) and 1.08% for plug-in hybrid electric vehicles (PHEV). The argument here for a continuing efficiency increase is that vehicle technology further improves and the weight is reduced because lighter materials are used in vehicle production. It is also assumed that the demand could shift to smaller cars in the future. We consider here BEV and PHEV as electric vehicles and categorise hybrid electric vehicles (HEV) as conventional cars since they cannot be charged. The share of HEV increases to 18.1% in 2050. The share of EV is still marginal. Pasaoglu et al. [39] expect that an EV share of 10% is possible. For the WTW emissions in 2050, we used the results of a scenario analysis [40] which estimated the exhaust emissions of different energy types. The scenarios achieved covered years up till 2030, so we interpolated the values for 2050. For the WTW emissions of electricity, it was assumed that the decrease would be 10% by 2050, which is a smaller decrease than in other scenarios. This very low reduction would occur if renewable energy is not exploited to the extent as it was initially expected and the use of fossil energy sources continues. One scenario in specific includes a sharp increase in renewable energy, which would then lead to substantially lower WTW emissions.

5. Decarbonisation Scenarios

In the process of developing decarbonisation scenarios assumptions were necessary concerning two aspects: about the type of measures or actions which reduce car emissions and about the magnitude of changes to the emission factors. It was supposed that each emission factor may have a substantial impact on decarbonising the car fleet or that it plays only a minor role compared to other factors. The spreadsheet model described in Section 3 was then used to quantify the needed change to each factor, with the condition that the emission target is reached. This constraint characterises the scenario definition process here as negative changes to one factor will have to be compensated by progressive positive changes to other factors. The following sections describe the steps of choosing suitable decarbonisation actions and assigning changes to emission factors.

5.1. Actions to Reduce Car Emissions

Having quantified the gap between the ‘business as usual’ case and the target level, it was now necessary to see how the emission factors vehicle fleet (F), car use (M), efficiency (F) and carbon intensity of energy (C) could be influenced in such a way that car emissions decrease. In a first step, we collected various actions proposed in other decarbonisation scenarios [10] and categorised them by emission factors. These actions are named as major levers in decarbonising car fleets. The list is not exhaustive and several further actions are possible. The list of actions in Table 2 however, provides a good starting point for developing the different scenarios.

Table 2. Actions to reduce car emissions and the targeted emission factor. Source: [10] and own additions.

Actions to Reduce Emissions	Emission Factor			
	(F)	(M)	(E)	(C)
Decouple travel demand increase from income growth	✓			
Higher tax on vehicle registration	✓			
Flexible car use through car sharing	✓	✓		
Improve non-motorised (cycling, walking), rail and public transport services (bus rapid transit, light rail, intercity high-speed rail)	✓	✓		
Restrict accessibility for cars in cities (Low Emission Zones)		✓		
Promote home office and deliveries		✓		
Reduce road and parking infrastructure		✓		
Increase driving costs (congestion charge, fuel taxation, parking charges)		✓		
Increase market penetration of EV, HEV			✓	
Improve material use in vehicle manufacturing processes			✓	
Shift to smaller cars and reduced engine power			✓	
Higher investments in EV charging stations			✓	
Speed regulation on highways			✓	
More automated driving tasks			✓	
Stricter emission standards			✓	
Reduce indirect emissions of electricity through renewable energy				✓
Raise share of next generation biofuels				✓
Introduce carbon capturing and sequestration (CCS)				✓

Those actions aimed at reducing car ownership (F) and car use (M) are supposed to either shift demand to alternative transport modes or to avoid the need for using cars. Restrictions in the use of

cars, for instance in city centres, may lead to more cycling or use of public transport. Measures such as higher taxation of fuels, vehicle use or parking fees will increase the driving costs, motivating car users to change to alternative modes. Car ownership will ultimately decrease as people decide not to buy cars anymore, due to the measures discussed above. When car use declines, the mobility system would ultimately shift towards more multi-modality, supported by sharing concepts, improved connectivity between different modes and investments in infrastructure of other modes. Actions leading to higher energy efficiency (E) and lower carbon intensity of energy (C) affect the fleet composition and the energy sector. An increase in the numbers of electric vehicles is said to be crucial to lowering fleet emissions and expanding the EV charging infrastructure. An increase in EV calls attention to decarbonising the energy sector as well, through a higher share of renewables for instance. Capturing emissions and storing them underground is offered as a solution to avoiding emissions from the use of coal power plants, which are still widely used in Europe [41]. In the end, it will most probably require a combination of the measures discussed here to reach a sufficiently large decarbonisation potential, and measures will have to target both levers of decarbonisation, car use and vehicle technology.

5.2. Transitions in Car Use

A transition towards more sustainable mobility will start with a pre-development phase in which few changes will be noticeable at first. As changes start to ‘take off’, they later accumulate so that the pace in which changes occur accelerates, leading ultimately to a breakthrough [42]. The transition pace then decreases in a ‘stabilisation phase’ in which a new equilibrium is reached [42]. Car use will have to go through such a transition on its path towards lower emissions in 2050. Should the ‘take off’ of new technologies or mobility concepts evolve slowly or be postponed, the timeframe up till 2050 might be too short to reach the desired emission level. Robinson [43] argues that a transition may take a full generation to evolve completely. Unexpected events, such as changes in environmental policy-making can accelerate or, in a worst-case scenario, further postpone the transition. Considering the actions proposed in the previous section, we can distinguish three dimensions when defining the scenarios: (1) the pace of technology transition, (2) the role of the car in future mobility and (3) the priority given to decarbonising energy supply. Considering the technical transition, we can distinguish between a slow and fast rate at which efficient vehicle technology evolves. Concerning the car’s future role in the mobility system, we can distinguish between a situation in which car ownership prevails and one in which car use is replaced by more multi-modal travel behaviour. The priority of low carbon energy indicates the extent to which efforts are being made to reduce WTW emissions of energy used for cars, from low priority to high priority. Each scenario is a combination of these three dimensions. A total of four scenarios were developed (Table 3). In the reference or ‘business as usual’ case, technology evolves at a slow rate, car ownership prevails in 2050 and low priority is given to decarbonising the energy supply.

Table 3. Framework for developing scenarios.

Pace of Transition	Developments in Car Mobility	
	Car Ownership Prevails (B1) ¹	Shift to Multi-Modality (B2)
Fast car technology transition (A1) ¹	Moderate (Scenario 1)	High (Scenario 3)
Slow car technology transition (A2)	Low (Reference case)	Moderate (Scenario 2)

¹ A1 and A2 affect the energy efficiency of vehicles, B1 and B2 the driving demand. The priority for decarbonising energy supply in each scenario is indicated as low to high in the arrays.

In the next section, each scenario is described and the respective decarbonisation strategies characterised. Table 4 includes the quantified changes related to the measures taken in each scenario.

5.3. Scenario Description

5.3.1. Reference Case

- Car ownership prevails
- Slow technology transition
- Low priority for green energy

The reference case is characterised by a constant increase in vehicle sales and a high driving demand. Overall car use has increased by 28%. The car remains the preferred mode for passenger transport and shifts to other modes will be marginal. The ongoing increase in demand for fast and large cars is constantly high. Car sharing in cities has not emerged to the extent that would substantially reduce car ownership. There are only occasional restrictions for conventional cars in cities, a fact which has failed to improve poor air quality. The car fleet has increased steadily as more people are able to afford a car, and vehicle taxes have remained moderate. Road capacity has been expanded to cope with the traffic increase, leading to very low travel speeds and high congestion. Most cars in the fleet are conventional cars because they have low driving costs. The vehicle efficiency of conventional cars has increased by just over 1% per year, which is a continuation of previous efficiency gains. No major leaps in technology developments have been achieved and only some driving tasks have been automated, due to drivers' strong preference for keeping control. The share of hybrid electric vehicles has increased to 18% (Table 4). Battery prices have only gone down slowly, which has led to a more recent increase in battery electric vehicles. The energy sector has fallen short of reducing emissions from energy generation. The share of renewables in the European energy-mix is still low, as further investments have not been deemed to be cost-effective. Emissions from fuel production have slightly increased because of lower availability of primary energy sources. The gains in energy efficiency have compensated the increases in both car use and WTW emissions so that overall, car fleet emissions have decreased by only 0.85% per year since 2010. Therefore, the White Paper target was not reached (Table 4).

Table 4. Results for scenarios.

Influencing Factors ¹	Base Case 2010	Reference 2050	Scenario 1: EV Dominates	Scenario 2: Shared Mobility	Scenario 3: Green Energy
Avg. mileage (km/vehicle)	13,325	13,054	13,054	16,056	12,270
Car fleet size (millions)	236	307	307	144	286
F × M (bn. vehicle-km)	3144	4009	4009	2318	3505
Share of conventional cars	100.0%	100.0%	3.0%	78.0%	66.0%
Share gasoline	60.2%	46.7%	0.7%	0.7%	0.7%
Share diesel	35.7%	31.2%	0.2%	0.2%	0.2%
Share CNG ²	0.5%	0.5%	0.5%	0.5%	0.5%
Share LPG ²	3.5%	3.5%	0.5%	0.5%	0.5%
Share HEV	0.1%	18.1%	1.1%	76.1%	64.1%
Share of electric cars	0.0%	0.0%	97.0%	22.0%	34.0%
Share PHEV	0.0%	0.0%	24.0%	18.0%	6.0%
Share BEV	0.0%	0.0%	73.0%	4.0%	28.0%
Consumption conventional/change per year (kWh/km)	0.704	−1.13%	−1.28%	−1.13%	−1.28%
Consumption electric car/change per year (kWh/km)	0.348	−1.03%	−1.19%	−1.03%	−1.19%
WTT emissions electricity (kgCO ₂ /kWh)	0.544	0.500	0.380	0.380	0.050
E × C (gCO ₂ /km)	247	129	57	100	65
Total emissions (Mt CO ₂)	777	515	230	230	230

¹ Included are only factors which are assumed to change compared to the reference case, others are equal to those in the reference case. ² CNG: compressed natural gas, LPG: liquefied petroleum gas.

5.3.2. Scenario 1: Electrification

- Car ownership prevails
- Fast technology transition
- Moderate priority for green energy

In the first decarbonisation scenario, the demand for car driving increases at the same rate as in the reference case. The total vehicle fleet has grown as in the reference case (+30%) which has led to 307 million cars in 2050. The strong transition towards electrification of drivetrains has substantially increased the number of EVs. The share of PHEV and BEV has reached 97% in 2050 the majority of which are battery electric vehicles. The transition was supported by higher taxes on conventional fuels, and EV manufacturers expanding their production capacities. Establishing a Europe-wide fast-charging infrastructure became a major target of transport policy-making, making it easier for EV owners to travel between countries. Autonomously driven vehicles have become a common picture in cities. Autonomous EVs search for charging stations and parking lots without any driver intervention. Some efficiency is lost to the fact that traffic density is high, which has called for additional road capacities to be built in the future. The average energy consumption of the European car fleet has considerably declined, due to both the electrification and the reduction in WTT emissions. The larger numbers of EVs has led to a significant growth in electricity demand. Investing in green electricity has become a major priority for European Union (EU) policy-making. Subsidies for constructing renewable energy plants have been directed to countries with high shares of fossil energy sources. This has required a common energy policy at a European level and the agreement to phase out fossil fuels in energy production. Due to these measures the average carbon intensity of electricity generation decreased by 30%. In Scenario 1 the targeted emission level in 2050 is met (Table 4).

5.3.3. Scenario 2: Shared Mobility

- Shift to multi-modality
- Slow technology transition
- Moderate priority for green energy

In contrast to the reference case and Scenario 1, the vehicle kilometres in Scenario 2 have decreased by 26% compared to 2010. This is not so much due to a reduction in car use, but rather to a substantial decrease in the car fleet, now consisting of only 144 million cars, a 53% reduction compared to the reference case. One major driver for this development has been the rigorous policy of limiting car access to cities. The growing urban population opted to ban gasoline and diesel cars from cities entirely and allow only electric or hybrid vehicles in city centres. The absence of conventional cars has led to a reduction of harmful exhausts and a general improvement of life in urban areas. Sharing cars has become a widely-accepted alternative to owning a car. Public transport providers have invested in their own EV fleets, to offer seamless connectivity at transport hubs where travellers are picked up for a shared ride. The occupancy rate of cars has increased and parking areas have been made available for alternative uses, due to there being fewer cars on the roads. The infrastructure for cycling was extended thanks to availability of road capacity. Energy efficiency improvements have been achieved mainly through the electrification of the car fleet, leading to a share of 22% EVs. The trend towards more automated driving slowed down after the demand for new cars starting decreasing. Automation had become a major technology trend for other transport modes since demand had shifted away from car use, to public transportation for the short distance and high-speed trains and air travel for the long distance. Travellers have become used to planning their trips far in advance, and to being picked up by shared rides from their own front door. Cars have become unnecessary for most daily tasks. The share of those working from home had increased substantially. As the share of EVs increased, the energy sector was urged to increase the share of renewable energy in the European energy-mix, to the same levels as in Scenario 1.

5.3.4. Scenario 3: Green Energy

- Shift to multi-modality
- Fast technology transition
- High priority for green energy

In Scenario 3 the transport sector is impacted by the fact that electricity which is practically carbon-free is now available. Concerns about energy security and the desire for higher independency from energy imports have led to a faster exploitation of renewable energy sources. WTT emissions of electricity have decreased by over 90% compared to 2010. The electricity distribution required high investments in the European energy grid, but opposition to it has remained weak. Carbon capture and sequestration has been applied to some extent in those countries relying on coal plants for energy production. The strong decarbonisation progress in the energy sector has relaxed the need for large changes in car use. The transport sector benefited from the cleaner energy which has reduced WTW emissions of EVs substantially. The share of conventional cars, however, exceeds the share of EVs. Due to the fast transition to automated driving, an increase in vehicle efficiency has been observed. Most driving tasks are now automated, leading to a more optimised use of speed and route choice. Car users have become accustomed to using travel time in cars for other purposes such as work or entertainment. Car rides are better connected to other transport alternatives, their main purpose having become the trip for the 'last mile'. Demand for car driving has reached a higher level compared to 2010, due to increased car ownership (21%).

6. Discussion

The scenarios developed here show that large changes are required if we are to meet the European Commission's White Paper target from 2011. The decarbonisation scenarios in 2050 were developed by using this target as a prerequisite for future low emission car mobility. Emissions were decomposed into four factors, in order to argue possible impacts related to the technology progress and mobility behaviour. A 'business as usual' case was developed, covering the baseline year of 2010 and the target year 2050, using reference data on car mobility, vehicle efficiency and carbon intensity of energy in the EU-27. The various scenarios show that the proposed changes could be really radical, and it would be difficult to imagine such changes being able to occur in the given timeframe.

6.1. Findings Related to Current Trends

6.1.1. Electrification of the Car Fleet

It is for instance doubtful whether there is enough time to realise a nearly complete 'electrification' of the EU-27 car fleet in 30 years' time as expected in Scenario 1. Figure 2 shows the composition of the vehicle fleet for each scenario. Conventional cars are replaced entirely by electric vehicles, their share being 97% of the total fleet, most of which are battery electric vehicles. Further technology improvements and a strong market uptake are necessary in order for BEV to become competitive compared to conventional cars in the upcoming decade. A milestone for EV's cost competitiveness is estimated to be reached, as soon as battery production costs decrease, from today's 500 US-dollars (USD) to around 150 USD per kWh [44]. Nykvist and Nilsson [45] assume that the targeted price could be reached in 2025. Berckmans et al. [46] consider battery prices of 100 USD per kWh possible for silicon-based batteries by then. Achieving this milestone could then really ignite the transition towards electrification. After 2025, there might be just enough time for a major transition, as described in Scenario 1, to take place. Today, EV sales are increasing at a very low rate in Europe, meaning that the 'take off' stage [42] for electrification is still in the future. Should the deployment of EVs be delayed, the window of opportunity up till 2050 could be too small for these high EV shares to be realised.

A less strong transition to battery electric cars is expected in Scenario 2. In this case, most cars are hybrids, accounting for over half of the fleet (Figure 2). Higher demand for hybrid vehicles will probably be the first step on the path towards a full electrification of the car fleet and the share of hybrids might be an indicator for the point that has been reached on this path. From this perspective, Scenario 1 would have almost reached the goal, while Scenario 3 would still be in transition and Scenario 2 lagging behind in fleet electrification. In Scenario 3, vehicle technology was argued to evolve fast. The high share of conventional cars in this scenario could lead to the conclusion that rather little technological progress is being achieved. Still, already a substantial part of the vehicle fleet consists of battery electric vehicles. The substitution of conventional cars has therefore taken place in a segment of the fleet, rather than on a broader scale as in Scenario 1. One reason for this might be that the electrification is first occurring in company car fleets. Nearly 50% of new cars in Europe are registered as company cars [47]. A fact which makes electric cars especially important to decarbonisation is the electricity which is practically emission-free, in Scenario 3. City authorities could take measures to force companies to use electric vehicles instead of conventional cars in cities, for air quality reasons. This would be in line with the carbon-free city transportation objective in Europe [4].

The scenarios did not cover fuel cell vehicles, even though hydrogen can be considered as a relevant energy alternative for the car fleet [25,48]. Disadvantages of fuel cell electric vehicles (FCEV), however, include their higher manufacturing costs and the expensive process of generating hydrogen. Also, biological additives to conventional fuels (biofuels) were not discussed as a decarbonisation alternative. Nevertheless, they could replace conventional fuels by 2050 [25] thus lowering WTW emissions of fuels compared to the numbers used here. The share of regenerative components in fuels reduces the carbon intensity, but the production of these components requires that agricultural land be used for energy production, which would then have to compete with land use for food production [49].

Considering these unsolved issues, the extent to which hydrogen and biofuels can further reduce car emissions is questionable.

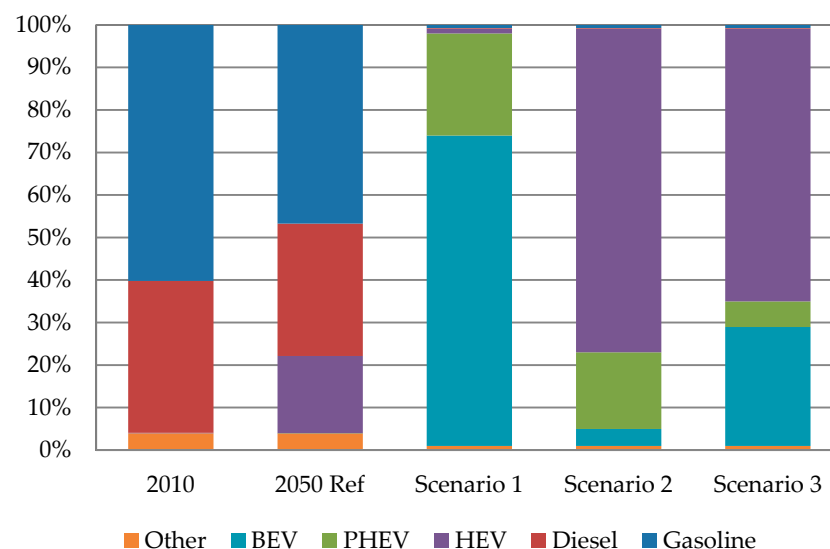


Figure 2. Car fleet composition, by vehicle type.

6.1.2. Patterns of Car Use and Ownership

In both the reference case and Scenario 1, the fleet size will continue to grow at similar rates to previous decades. In 2050, the fleet will account for 30% more vehicles compared to 2010. After a long period of increasing numbers, car sales dropped after 2008, due to the financial crisis, but continued to increase again in the years after. An ever-increasing vehicle fleet will ultimately require more road capacity and parking space in densely populated areas. It can be assumed that this will lead to bottlenecks in cities where congestion is high. It could be that more cars on roads would lead to strong protests from people living in cities. The acceptable limit of congestion might be reached at any point between today and 2050. A useful indicator for car ownership is the motorisation rate (Figure 3), which is around 473 cars per 1000 inhabitants in the EU-27 [20]. In both the reference case and Scenario 1, the rate would increase to 589 cars, assuming a 4.5% population growth rate until 2050 [8]. This is a far higher rate than in Germany, Belgium, France or the United Kingdom and is close to the rates in Malta and Luxembourg [20] but still substantially lower than in the United States [50]. In countries with a high motorisation rate the population is more dependent on car use as transport alternatives are not available to most people. A path of a high car ownership could mean just this, that many have become dependent on using a car for their daily mobility.

The future mobility system has to adapt to the expected population growth. Fiorello et al. [8] forecast a constant increase until 2050. The question however arises what the consequences could be if more people live in Europe by 2050 than predicted. The demand for car driving increases if the European population increases more than predicted and more people decide to drive cars. As a result, car emissions would increase too. The gap between the BAU case and the emission target becomes larger. More drastic measures than those proposed in the scenarios might become necessary. A stronger population increase than predicted could worsen the traffic situation in cities. The increasing urban population requires alternatives to car driving, which should receive a high priority if the number of transport users increases disproportionately. Assuming that the population does increase according to present forecasts and new mobility patterns evolve, car use could become less relevant to the mobility system in 2050. A ‘car peak’ could even be reached soon, as argued by [51]. Scenarios 2 and 3 support this assertion. Cars do not play a similarly dominant role in these scenarios, compared to the reference scenario. If cars are less frequently used, this will lead to less ownership and lower motorisation.

In Scenario 2, the motorisation rate is 265 cars and in Scenario 3, 548 cars per 1000 inhabitants (Figure 3). Such a large shift away from car use as in Scenario 2 is unprecedented, considering the shift rates of previous decades [18]. This would imply major changes in travel behaviour, possibly motivated by measures to increase driving costs. The structure of the traffic network would also change, if road capacity were no longer needed. Space becomes available for cycling lanes or footpaths, leading to a positive impact on the quality of life in urban areas [52,53]. Commuting could be reduced, as mobile internet access allows working remotely from home, reducing the need for daily commuting by car. Åkerman and Höjer [52] and Creutzig [54] argue that use of information and communication technologies (ICT) could be a strong driver for reduced car mobility in the future. On the other hand, if people spend more time at home, this might result in further energy use for other purposes. Spending more hours at home leads to more energy use in the household, for heating or using ICT for instance. If the demand for home deliveries increases, it raises the trip number of commercial transportation, for which then low carbon alternatives become necessary.

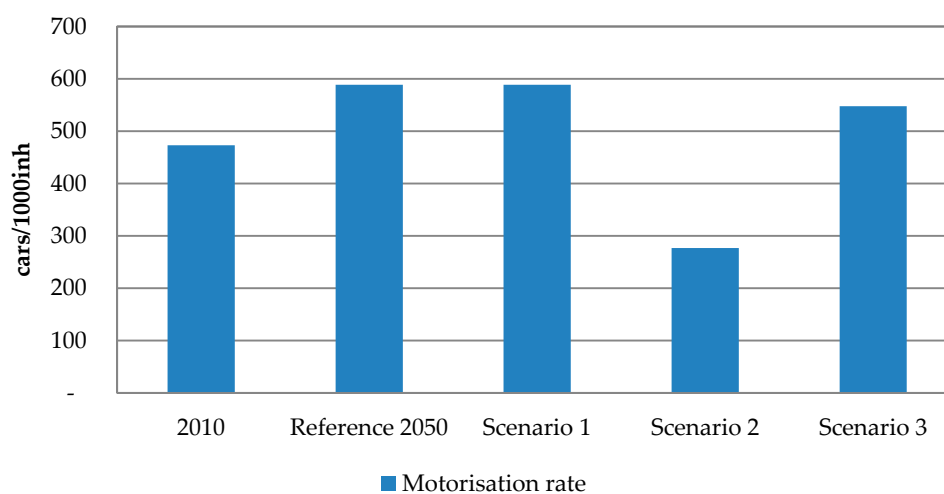


Figure 3. Motorisation rate in scenarios. Source: Fiorello et al. [8] for EU-27 population, number of vehicles from scenarios.

In real-world conditions, the reduction of cars on the road would almost certainly lead again to more car mobility. One possible solution for tackling this problem, besides further raising driving costs, is to improve the availability of alternative modes. Air and rail travel are expected to increase in the future, more strongly than car use. Air travel is becoming a cost and time efficient alternative for longer trips. The emission intensity per passenger-kilometre of air travel is higher than the intensity for passenger cars [8] which increases the necessity to further improve the energy efficiency of aircrafts in the future. Metz [51] and Creutzig [54] argue that cars could become also less relevant for short trips, as the share of people living in cities increases. They conclude that demand for short distance travel will in this case shift to public transportation or train travel. As car use becomes a weaker driver for transport emissions, the carbon intensity of other modes becomes increasingly relevant. The carbon intensity of rail travel is relatively low. Energy consumption and emission levels from air travel depend on the aircraft type and the altitude. The overall atmospheric impacts of air travel, however, are still not entirely known [12]. In the context of the discussion on emission savings from mode shifts, it is important to point out that shifting demand from car driving to other modes will not solve the overall transport emission problem. However, it can have a positive effect if fewer people depend solely on car use for their everyday mobility, as this would not be in the interests of a sustainable transport policy. More progressive investments in public transport sector, for instance, may be required to reach this objective [55].

6.2. Scenario Analysis and Backcasting

6.2.1. Analysis of Decarbonisation Scenarios

Scenarios can be considered useful instruments for the description of unconventional solutions, including those based on ‘rigorous’ assumptions. As [56] puts it, scenarios can point out extremes among possible alternatives, and thus trigger new ideas for problem-solving processes. Backcasting is an especially useful approach to analysing scenarios for future transport systems [11,57] or subsectors [12]. The present approach did not consider the effects from mode shifts, which would have required a quantification of emissions in other sectors as well. Such effects are relevant to the estimation of overall transport emissions, for which the European emission model TREMOVE is used.

The present approach was limited to an assessable number of key emission factors which were then used to analyse the driving forces for decarbonisation of the EU-27 passenger car fleet. The quantification method used here may be a simplification of the complex system of interrelated factors of car emissions, but in this approach, it served to calculate the changes needed. Interrelations between factors occur. It is likely that cars which are more efficient will result in more car use. This rebound effect was studied for instance by [58]. Another unintended effect appears when higher shares of EV raise the demand for electricity which would then probably have to be generated using more fossil energy sources. Sinn [2] argues, that a restrictive decarbonisation policy could ultimately lead to more emissions if the exploitation of fossil sources is not regulated, an effect he calls the green paradox. It is of great value that such unintended effects be identified early in decision-making processes and, if possible, quantified using the appropriate tools and models [59].

Furthermore, in order to gain knowledge about priorities and preferences related to them, it is of great value if expert judgement and stakeholder participation can be integrated in the discussion of decarbonisation strategies. Fostering the participation of actors who are affected by progressive decarbonisation measures increases the possibility that these alternatives are implemented successfully later on, and eventually reduces uncertainties linked to the proposed actions [60]. Assessing stakeholder preferences towards a set of alternatives can help to identify those alternatives which have a high implementation potential. An approach considering stakeholder preferences is, for instance, the Multi-Actor-Multi-Criteria Analysis (MAMCA) which provides a structured procedure to evaluate technological alternatives [61] or to analyse different sustainability measures [62]. Applying such an analysis on decarbonisation scenarios would help discovering those stakeholder needs and requirements which favour or prevent a fast technology transition, a shift away from car driving or an accelerated uptake of renewable energy sources.

6.2.2. Limitations of the Approach and Potential Developments

The approach chosen here is characterised by the assumptions about relative changes between emission factors, about how much one factor needs to compensate for changes occurring to other factors. One could argue that such interdependencies and the magnitude of changes to these factors require more evidence about their feasibility. For each decarbonisation scenario a certain combination of factors related to the composition of the future car fleet, mobility behavior and energy system was chosen. It is difficult to estimate whether and when these changes might be reached since they are surrounded by a number of uncertainties. For instance, stricter legislation requires acceptance by society first and it needs to be seen when electric vehicles will ultimately become a dominant technology on vehicle markets. One could also argue that car-sharing will play only a minor role for fleet decarbonisation as it is limited to city transportation. A further development of the present approach should include a validation step with quantitative methods to support or reject the assumptions behind proposed changes to emission factors. A similar exercise was carried out by Hickman and Banister [11] where focus groups were used to evaluate scenario results and by Banister et al. [1] where, in context of an European research project, quantitative changes were combined with transport policy measures during the scenario definition process. Integrating more qualitative information would certainly

improve the scenarios and increase their degree of reality. Another limitation of this approach is that the data for calculating the scenarios was retrieved from rather few data sources which implies that the quality of this data is dependent on the quality of the data sources. The information was however compared *ex ante* with numbers for national car fleets, but it showed to be difficult to make a reliable comparison with the more aggregated car fleet data for Europe. To further refine the approach, it could be an advantage if the data basis behind the emission factors would be disaggregated to the country level which would make the results more precise. The calculation of emissions could thus first happen on country level and the results would then be summed up to estimate if the emissions target is reached on a European level.

7. Conclusions

Decomposing car emissions into factors and quantifying their decarbonisation potential proved to be a useful approach to analysing the changes required to meet the White Paper target. The scenario results showed that changes will have to be comprehensive. This is the case if either mobility or efficiency fails to contribute sufficiently to the decarbonisation of car use. If the energy sector reforms and renewable energy become widely available, a strong opportunity will open up for the decarbonisation of the car fleet. A transition to electric cars is necessary in any case. The leap in EV deployment as discussed in Scenario 1 might be too progressive and fail to materialise. However, the results show what could happen if car mobility continues to increase as in the ‘business as usual’ case: a share of 97% EV might be necessary by 2050. On the other hand, if transport demand shifts to other modes then there will be less need of electrification and the fleet could continue to have a high share of conventional cars and a medium share of hybrids as in Scenario 2. The more desirable option is that changes to mobility and efficient technology could both contribute to lower car emissions, so that no extreme strategies have to be followed. Scenario 3 would be a much more balanced option, from a transport sector point of view. Vehicle kilometres would not change as much as in the other scenarios and conventional cars would still play a major role. The green electricity in this scenario makes it the one in which the biggest steps to reduce GHG impacts are made in the energy sector, and where the transport sector profits from it. This also shows how relevant the decarbonisation of energy is for goal-setting in the transport sector.

The scenarios describe different futures of the European car fleet in 2050 which include different assumptions about the way we will use cars in these futures. For the implementation of appropriate actions and policies it is necessary to choose a decarbonisation pathway that also considers the many uncertainties which are linked to it. Marchau et al. [63] state that uncertainty is often neglected or ignored in transport analyses which assess the impacts of alternative actions. They point out that upcoming technology breakthroughs, demographic developments and changed mobility behaviour represent trend breaks which will alter the predictions that we make today. Marchau et al. [64] speak of decision making under ‘deep uncertainty’ when one can neither predict, if such an event will take place nor what magnitude it might have. Analysing decarbonisation scenarios can serve as starting point for identifying uncertainties which can then be addressed with appropriate policies and actions. In this context Haasnoot et al. [65] point out that the development of a decarbonisation pathway should include the possibility to react on changes occurring over time and to adapt the initial approach. New challenges and opportunities for decarbonising the European car fleet will occur when, for instance, automated cars become available. As it is impossible to foresee when this is going to happen in the future, the assumed trends should be constantly monitored and such points in time should be defined in advance. By doing so current policies can be evaluated and, if necessary, be adapted considering the new trends. Such adaptive policies [64] and the respective pathways [65] are able to address the uncertainties related to the development of future trend and thus improve the possibility to reach the emission targets.

The uncertainty about developments in the energy sector and the respective policy making plays a crucial role when identifying a feasible decarbonisation approach for the car fleet. Without

member states agreeing on a common strategy for the transport and energy sector, achieving the 60% target for the entire European car fleet will be ambiguous. For countries with high resources of fossil energy, national interests could negatively affect the motivation to shift to cleaner energy. Such national objectives gain in importance in times of political scepticism. However, right now it is especially important to foster the deployment of more renewable energy and reduce the dependency on fossil energy which is, to a large extent, imported from outside the EU. It remains to be seen if countries are willing to collaborate on the achievement of the common goal defined in the White Paper. The challenge for countries with a strong automotive sector is to transfer jobs from conventional car manufacturing to new areas such power electronics or information technologies (IT). Market leaders are then evolving in those regions where competitive technology meets the demand for it and where jobs are created in areas of future car technology.

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Appendix A

Table A1. Data sources for baseline and scenarios.

Emission Factors	2010	2050	Data Source
Average annual mileage (km/car)	13,325	13,054	Average value for 2010: [19,29–32] Increase for 2050: [19]
Vehicle fleet (number of cars)	235,947,849	307,145,288	Average value for 2010: [8,14,20,23,33] Increase for 2050: [19]
Vehicle efficiencies (kWh/km) of			
Gasoline	0.830	0.422	Values for 2010 and 2050: [19]
Diesel	0.744	0.402	
HEV gasoline	0.623	0.334	
HEV diesel	0.558	0.318	
PHEV gasoline	0.410	0.233	
PHEV diesel	0.374	0.231	
EV	0.225	0.147	
LPG	0.769	0.429	
CNG	0.704	0.414	
Electric proportion in PHEV (%)	30%	70%	
Fuel proportion in PHEV (%)	70%	30%	
Fleet share (%) per engine type			
Gasoline	60.20	46.71	Values for 2010 and 2050: [19]
Diesel	35.73	31.17	
HEV gasoline	0.07	10.86	
HEV diesel	0.06	7.28	
PHEV gasoline	0.00	0.01	
PHEV diesel	0.00	0.01	
EV	0.00	0.00	
LPG	3.48	3.46	
CNG	0.46	0.50	

Table A1. Cont.

Emission Factors	2010	2050	Data Source
Indirect emissions (kgCO ₂ /kWh)			Values for 2010: [36] Interpolated increase for 2050: [40]
Gasoline	0.0497	0.0527	
Diesel	0.0554	0.0551	
Electricity	0.5440	0.5000	
Hydrogen	0.4271	0.4271	
LPG	0.0288	0.0345	
CNG	0.0468	0.0414	
Direct emissions (kgCO ₂ /kWh)			Values for 2010: [36] Interpolated increase for 2050: [40]
Gasoline	0.2639	0.2797	
Diesel	0.2542	0.2526	
Electricity	0.0000	0.0000	
Hydrogen	0.0000	0.0000	
LPG	0.2365	0.2836	
CNG	0.2027	0.1793	

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