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Heading towards low-carbon passenger car mobility: electricity vs hydrogen

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Abstract: Due to pressing environmental issues, the need to head towards low-carbon mobility is growing. Battery electric- and fuel cell vehicles are considered to contribute to decarbonize the transport system. The core objective of this paper is to discuss the role of electricity and hydrogen in the decarbonization of passenger car mobility. Firstly, the recent developments of battery electric and fuel cell cars are described. Next, their environmental and economic performance is analyzed in a dynamic scenario up to 2050 for the average of EU-15 countries in comparison to conventional vehicles considering total costs of ownership and possible technological learning, as well as all relevant emissions. The major conclusions are: (i) Battery electric- and fuel cell vehicles could have environmental benefits in comparison to conventional cars, if electricity respectively hydrogen used is produced from renewables. (ii) The economic competitiveness of battery electric- and fuel cell vehicles has been increasing over time due to technological learning. (iii) However, despite the fact that there may be significant progress regarding these alternative automotive technologies, they will not solve all problems. It is obvious that also other strategies are necessary to head towards a sustainable transport sector.

Keywords: electric vehicles; fuel cell vehicles; battery; emissions; costs

1. Introduction

Due to increasing car ownership rates and travel activity all over the world, energy consumption in the transportation sector is continuously rising, and is responsible now for about one quarter of global energy consumption. This is almost completely provided by fossil fuels causing significant amount of greenhouse gas (GHG) emissions [1]. In the EU, as shown in Figure 1, GHG emissions from the transport sector are growing unlike all other sectors.

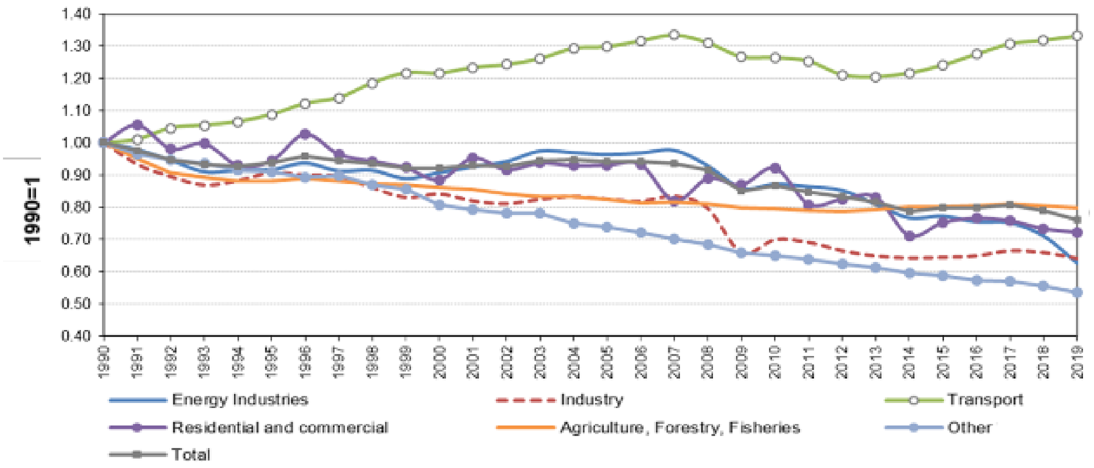

Figure 1. Development of relative GHG emissions by sector in the EU-27 from 1990 to 2019 with respect to the level in the year 1990 [2].

To cope with the increasing GHG emissions, use of different alternative energy carriers and automotive technologies is widely promoted by policy makers, and critically discussed in scientific papers.

Various efforts have been made in previous works towards clarifying technical performances of alternative vehicle technologies [3–5], their economic- and environmental aspects [6–9], relevant supporting policies [10], as well as their historical developments and future prospects [11,12].

The major alternative fuels and automotive technologies, which currently have the potential to contribute to the decarbonisation of the transport sector, are shown in Figure 2.

Biofuels are already widely used and well established in passenger car transport [13]. However, currently used 1st generation biofuels are limited in their contribution to the reduction of GHG emissions per kilometre driven as well as in total potential. For the production of biofuels, the mostly used sources are agricultural feedstocks, such as wheat, corn, rapeseed, soybeans. Yet, the areas used for growing these feedstocks are also usable for food and feed production. Increasing demand for these feedstocks due to biofuel production can trigger competition between fuel and food production, and in a direct or indirect way a land use change, leading to possible negative environmental impacts. In addition, due to the bans announced on internal combustion engine (ICE) vehicle sales in different countries, (e.g. in Norway starting from 2025), it can be expected that the interest in the use of conventional vehicles will decrease in future. Consequently, also demand for biofuels in passenger car transport could be significantly reduced. The future role of biofuels is largely dependent on the possible development of non-food based, second generation biofuels from waste and lignocelluloses, as well as policy targets and supporting policy framework.

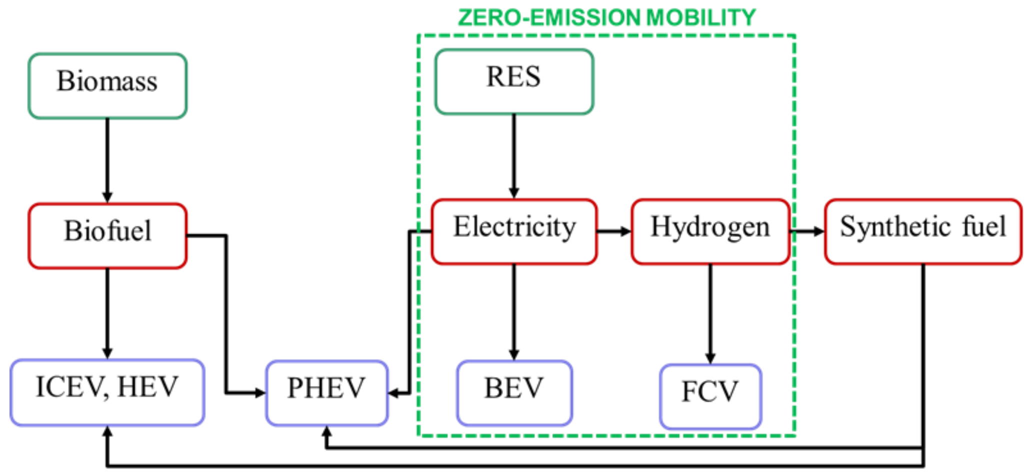

Figure 2. Alternative powertrain technologies and energy carriers for low carbon mobility (adapted from [14]).

A major problem related to synthetic fuels is their low total efficiency because of high energy conversion losses in the overall conversion chain, see Figure 3, leading to high production costs. Currently, synthetic fuels are mostly produced in pilot plants. The bans on ICE vehicles will also have negative impact on use of synthetic fuels. Due to all these reasons from the current point of view, in the mid- and long term most favourable alternatives to fossil fuels will be electricity and hydrogen, which can be used in zero-emission vehicles.

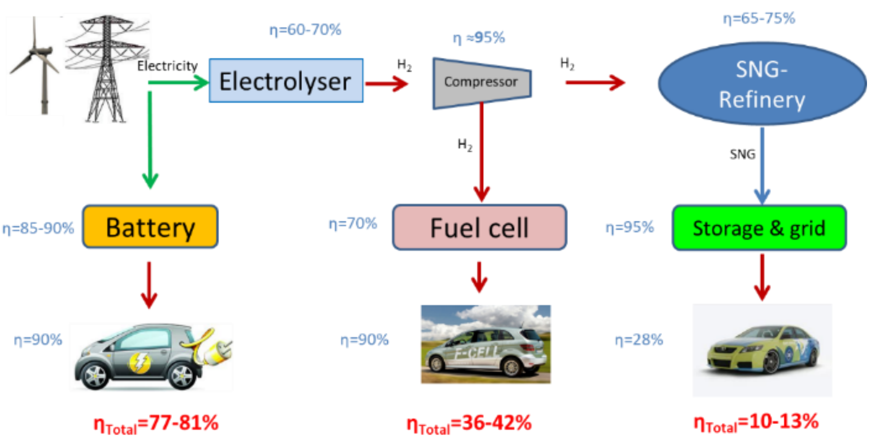

Figure 3. Overall energy conversion efficiencies of different alternative vehicle technologies (data sources: [14–16]).

Therefore, over the last decade, special focus has been put on the electrification of mobility [17]. In most of the European countries, beside the policies implemented at the EU level, which indirectly support electric vehicles, such as standardization of CO_2 emissions from the new passenger cars, also different dedicated promotion measures for electric vehicles (EVs) have been provided. These measures can be divided in two categories: (i) monetary measures such as subsidies, tax reductions or exemptions, and (ii) non-monetary measures such as possibilities for EV drivers to have free parking spaces, to use bus lanes, or to enter city centres and zero-emission zones. Due to these supporting policies, the number of electric vehicles has significantly increased over the last few years. However, the future deployment of e-mobility is very dependent on the further development of their economic and environmental performances.

The economic and environmental performances of different types of electric vehicles are already analysed and discussed in literature. An important contribution is provided by Bubeck *et al.* [8]. They have analysed the total costs of electric passenger cars using a component-based approach and focusing on the German market. An additional contribution to costs and environmental impact of mid-size battery and fuel cell electric vehicles in Germany is conducted by Bekel and Pauliuk [18] Wróblewski *et al.* [19] has analysed the development of the e-mobility market as well as the market demand for hydrogen fuel cell vehicles in Poland. This research was based on a numerical experiment. Contestabile *et al.* [20] have reviewed several studies on alternative transport technologies concluding that it is difficult to make comparison due to the use of different performance indicators for fuels and powertrains. For example, Duigou and Smatti [21] calculate total costs of ownership of battery electric vehicles considering yearly mileages of 30 000 km what is much higher than European average.

In contrary, to many papers which are focusing on one specific country (*e.g.* as mentioned above Germany or Poland), we have conducted our analysis considering the average conditions in the EU-15 using most recent data. This is beneficial for the discussion on economic and environmental issues of e-mobility since the costs of energy, carbon intensity of the electricity mix, as well as policies implemented are changeable over time.

The core objective of this paper is to analyse the potential role of battery electric vehicles and hydrogen driven fuel cell vehicles in the decarbonisation of passenger car mobility for the average of EU-15 countries. A special focus is put on the analysis of their environmental and economic performance in a dynamic scenario up to 2050 in comparison to conventional fossil fuels used in internal combustion engine (ICE) vehicles. In this framework the major issues considered are: (i) technological learning regarding the investment costs, (ii) technological innovation for efficiency, (iii) dynamics of the electricity generation mix towards higher shares of renewables and (iv) the reduction of embedded GHG emissions of cars due to improved processes up to 2050. The consideration of these dynamic effects simultaneously is the major unique aspect of this study and the major research gap addressed. The analysis starts with the documentation of the state of the art of battery electric- and fuel cell vehicles. In addition, the major barriers for their broader market penetration are identified. Next, an economic and environmental assessment is conducted in comparison to conventional ICE vehicles in a dynamic framework up to 2050. The environmental assessment includes discussion on three major aspects: (i) embedded CO_2 emissions in car production and assembly; (ii) the role of the primary energy sources used for electricity and hydrogen production, and (iii) the dynamics expected for the environmental aspects.

2. Electric vehicles

Over the last decade, electrification of mobility has been seen as one of the major strategies for the decarbonization of the transport sector. Many studies have discussed possible benefits of electric vehicles, as well as major obstacles for their faster market penetration [22,23].

Although, currently the focus is put on the electrification of the passenger car mobility, other e-mobility technologies, such as trains and trolleybuses, are already mature technologies with a long history [24,25]. The electrification of the road transport, especially passenger cars, has intensified over the last decade, mostly due to supporting policies. The number of the new EV models in all car segments is rapidly increasing. All currently available EVs can be classified in four major categories: hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). A more detailed description of these vehicles is provided in [11].

Since HEVs cannot be charged externally, they are completely dependent on fossil fuels, they can be seen just as more energy efficient conventional ICE vehicles. Currently, most relevant are rechargeable EVs such as PHEVs and BEVs. The development of the global EVs stock is shown in Figure 4.

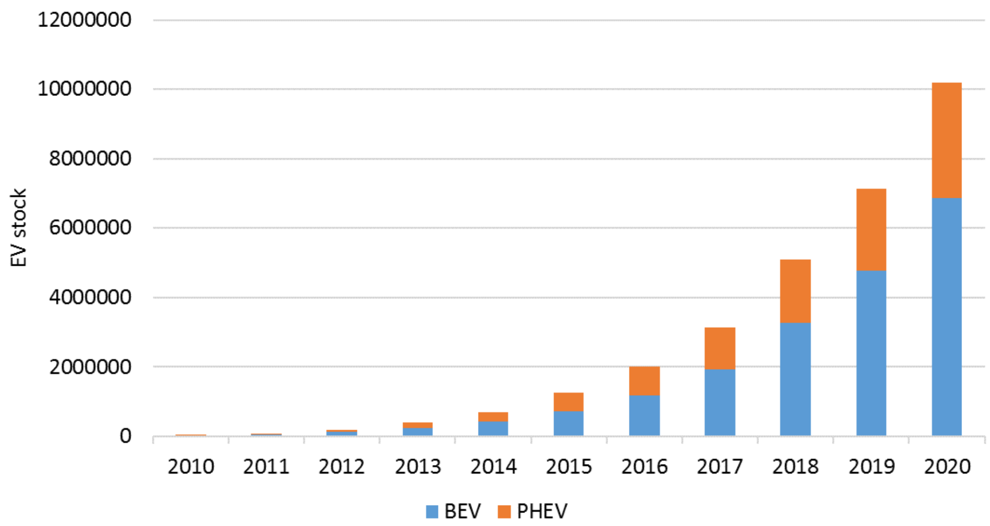

Figure 4. Development of the global EV stock, passenger cars (data source: [26]).

Despite increasing number of EVs over the last decade, their total number is still very low in comparison to the total vehicle stock. Currently, the largest number of EVs on the roads is in China, followed by Europe and USA [27].

In general, major benefits of electric vehicles are high energy efficiency, reduction of local air- and noise pollution, which is of special interest for large urban areas. Moreover, electric vehicles have potential to reduce the GHG emissions depending on the selected energy supply changes. The final goal is to provide e-mobility using electricity generated mostly from the renewable energy sources (RES).

However, as with most technology, electric vehicles also have some disadvantages. According to the Climate Group's EV100 Initiative, which brings together over 100 companies in 80 markets committed to the electrification of the transport sector, five major obstacles for a faster deployment of EVs are: (i) the high capital costs, (ii) the lack of charging infrastructure, (iii) long charging times, (iv) the limited number of vehicle models, and (v) a changeable policy framework [27,28]. However, besides these most well-known and obvious barriers there is a broad portfolio of challenges related to the materials used in batteries, as well as appropriate battery recycling.

Currently, lithium-ion batteries are the dominant technology for EVs but also for some other applications such as mobile phones, laptops, tablets, etc. In batteries, lithium is used in combination with other materials such as cobalt, nickel, graphite, aluminium and copper [29,30]. Due to the fast growth of the battery market, mostly due to EVs and information technology, the demand for battery materials is increasing. Such development leads to supply, environmental and social risks due to geographical concentrations and the limited availability of major battery materials, as well as negative social and environmental impacts related to material mining [31–34].

The lithium mining requires considerable amount of energy if lithium have to be extracted from rock or huge amount of water if lithium have to be extracted from brines [35]. Some estimates show that about 2 million litres of water are needed per one ton of lithium [36]. More than half of the world's lithium resources is concentrated in Argentina, Bolivia and Chile. Already, at current stage lithium mining in South America is associated with groundwater depletion, soil contamination and other forms of environmental degradation [36,37].

Even worst is the situation with cobalt, which is largely concentrated in the Democratic Republic of the Congo. According to UNICEF, about 40000 children is involved in cobalt mining. They work in extremely dangerous conditions, which can cause different health problems. Besides these social concerns cobalt mining could cause acid mine drainage posing serious risk for rivers and aquatic life [36].

Actually, the mining of all materials used in battery production raises social and environmental concerns, and growing battery production due to the electrification of mobility, could make these problems even worse.

However, it is important to note that battery technology is evolving and new chemistries can be expected in the future [30,38]. On the one side, total amount of materials used in battery production should be reduced and the most hazardous materials should be replaced with safer one. In addition to this, appropriate battery recycling should reduce the dependency on mining and refining as well as negative impact on environment. Yet, currently there are no large-scale lithium-ion batteries recycling methods in use due to the high upfront investment costs and high price of recycled materials in comparison to mined equivalents on commodity exchanges [37,39–41]. All these challenges will be even more visible with the increasing number of EVs.

For now, one of the major impediments for the broader use of EVs is their high purchase price, which is largely dependent on the battery capacity. The current technology on battery packs requires a trade-off between driving range, which is dependent on battery capacity, and total weight of vehicles. However, due to the significant progress and improvement of battery performances, battery costs have been continuously decreasing over time, see Figure 5. This development should make electric vehicles more competitive on the market.

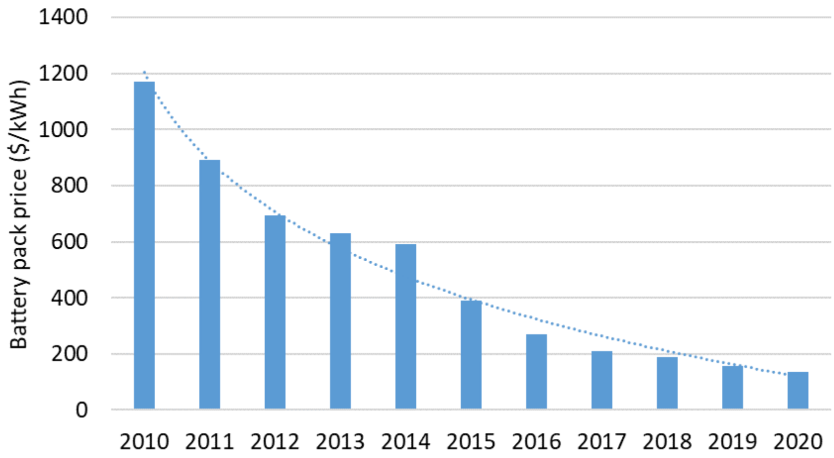

Figure 5. Development of the average battery pack prices (data source: [42]).

With the increasing use of EVs, a similar trend can be observed in the number of charging stations but the majority of the charging infrastructure is still concentrated in a just few countries and regions, mostly those with high gross domestic product (GDP) [43].

3. Fuel cell vehicles

Although the idea to use hydrogen in the transport sector is very old one, hydrogen and fuel cell vehicles are still seen as a long-term option for mobility. Some of the major reason for this are high costs, lack of infrastructure and some technical barriers such as reliability and durability [44–46]. Due to the combination of all these reasons, the penetration of fuel cell vehicles in the market is very slow. As it can be seen in Figure 6, the number of FCVs has been increasing over the last years but the total number is very low even in comparison to other types of electric vehicles.

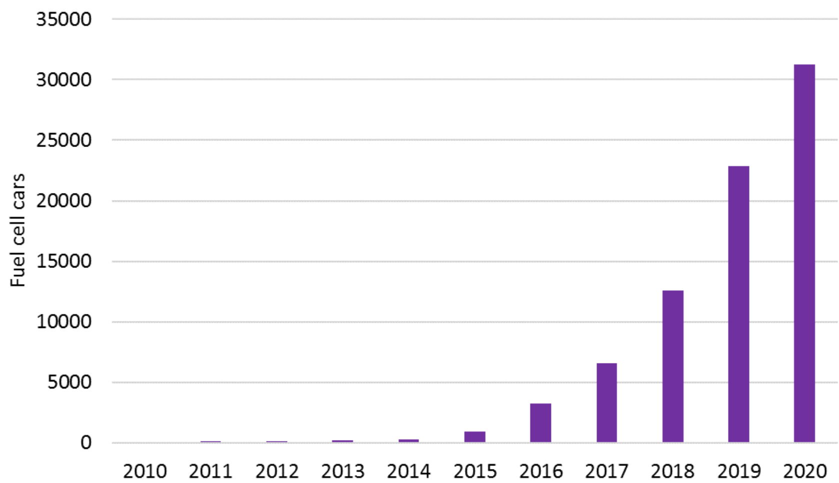

Figure 6. Stock of fuel cell vehicles (data source: [26, 47]).

In 2020, there were just about 31 000 FCVs in use, most of them in four countries: Korea, USA, Japan and Germany, see Figure 7. Currently, fuel cell vehicles are expensive mostly due to the low production volumes and manufacturing-cost associate to fuel cell system [48]. Although, in the production of FCV some raw materials are used such as platinum, they represent just about 20% of the total manufacturing costs [49,50]. The amount of platinum used in FCVs is currently just about 10-20 grams per vehicle [48]. However, since platinum causes different environmental impacts, such as sulphur oxides emissions produced during the extraction of the material [48], it is important that platinum use in fuel cell is significantly reduced over the last years. For example, Daimler has cut platinum content in its FCVs by 90% since 2009. Moreover, reduced material use in combination with increased production should make FCVs more competitive with BEVs, as well as with conventional cars.

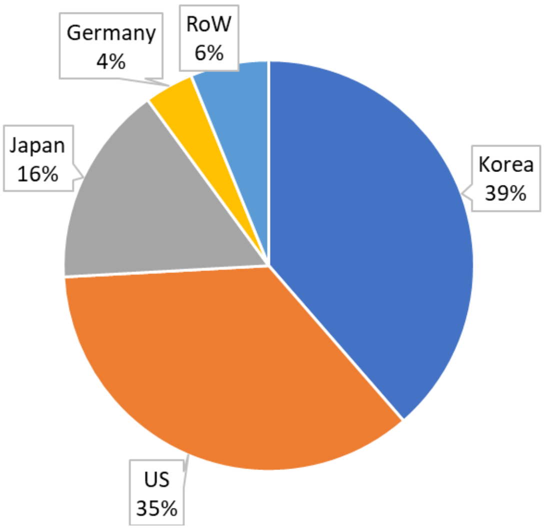

Figure 7. Share of FCVs in 2020 by country (data source: [47]).

Although, high costs of FCVs [50–52] and lack of hydrogen infrastructure [45,53] are mostly discussed barriers for the faster deployment of FCVs, the additional barrier are some technical issues related to fuel cells. For the future, it is important to increase durability, reliability and robustness at the stack scale combing better design and materials, as well as better water and thermal management [54]. As per previous studies, a fuel cell stack is much more vulnerable to degradation compared to a single fuel cell [55,56]. Low durability and reliability could be caused by degradation of materials due to water and heat issues [57,58]. The technical feasibility is one of the critical issues for commercialisation of FCVs [54].

The reason for optimism for the faster deployment of hydrogen and FCVs is the fact that hydrogen is not just an energy carrier, which can be used in the transport sector, but an energy vector for applications ranging from the small-scale power supply in off-grid modes to large-scale chemical energy exports [59]. Currently, due to increasing use of renewable energy, hydrogen's role as an energy storage for the surplus electricity from RES is becoming more and more important [60]. Therefore, the true potential of hydrogen is not just its ability to reduce emissions in the transport sector but also to generate additional benefits in the long run through different use purposes.

4. Methods

The future use of BEVs and FCVs is dependent on the development of their economic performances, as well as their possible contribution to emission reduction. In the following, the methods for the economic and environmental assessment are presented.

4.1 Economic assessment

In this paper, the total costs of ownership (TCO) are calculated for BEVs and FCVs in comparison to conventional ICE vehicles. TCO is defined as "a purchasing tool and philosophy which is aimed at understanding the true cost of buying a particular good or service from a particular supplier" [61]. It is the sum of all costs associated with acquiring and running of vehicles over its deprecation time [62]. It is usually expressed in a cost per kilometre. The TCO method is widely known and applied in literature, see *e.g.* Bubeck et al [8] who also provides a very comprehensive overview of the literature using this approach.

TCO includes both the purchase price of vehicles and their corresponding operational costs [63]. In the following calculations the focus is put on the average European car segment C – midsize cars with 80kW power and corresponding 55 kWh battery for BEV [64–66]. Although, BEVs are available in all car segments, in smaller segments is their driving range too short in comparison to conventional cars and in the larger segments their investment costs are too high in comparison to conventional cars [67]. The values for the four vehicle types analysed are documented in Table A1 in the Annex. The investment costs are used on the base of 2020 costs including a European average of 20% value add tax (VAT). In this study we use the over-all purchase prices of vehicles including all vehicle cost components (*e.g.* costs of engine, battery, fuel cells, hydrogen tank, etc.). To obtain the annual capital costs, the capital recovery factor (CRF) is used, as shown in eq. (1), assuming 5% interest rate and a depreciation time of eight years for all vehicle types. In the EU average age of vehicles used in 2020 was 11.8 years. However, there are significant differences between countries. In countries with the higher GDP per capita average age is between 6.7 (Luxemburg) and 11.8 (The Netherland) years, and majority of zero-emission vehicles is currently used in these countries [68]. Moreover, most automakers have an 8 to 10-year warranty period on their batteries [69, 70]. Considering this, a battery replacement or re-investment in any other car component is not included in our analysis.

The fuel costs depend on the fuel price, the corresponding taxes and the energy intensities of the cars. The energy intensity (EI) represents the average of energy use per 100 km based on statistics and own estimations for passenger cars with 80 kW capacity in 2020. Note that in this analysis no differentiation between the urban and extra-urban driving has been made as *e.g.* presented in [8]. The values used for EI are also documented in Table A1.

In addition, the prices of energy used – gasoline, diesel, electricity or hydrogen – are of interest. The figures used are an average for the years 2018 to 2021 for Western European countries. The prices include all taxes (VAT, excise tax) and the net fuel price. For the year 2020 an average excise tax is used and a VAT of 20%, as documented in Table A1. Of course, energy prices as well as corresponding taxes are changeable over time. In our scenarios the introduction of a continuously rising CO_2-based tax is assumed, starting in 2025 with 0.1 €/litre diesel and gasoline and increasing by this amount every year up to 2050. It ends up by 2050 at 2.5 €/litre fossil fuel leading to a significant increase of diesel and gasoline prices over time. Since total mobility costs are calculated per kilometre driven and year, interest rates, depreciation time and the specific number of kilometres driven per year have an impact on total costs. Moreover, average yearly operating and maintenance costs are considered.

The total costs of ownership (C_{TCO}) for different vehicle technologies and different energy carriers (j) per km driven are calculated for the average of EU-countries using the following equation [11]:

$$C_{TCO_j} = \frac{IC_j \cdot CRF}{vkm} + P_{E_j} \cdot EI_j + \frac{C_{O\&M_j}}{vkm} \quad (1)$$

with

$$CRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (2)$$

Where **IC** is the investment cost of vehicle; **i** is interest rate; **n** is the depreciation time; **vkm** is the specific number of vehicle kilometres driven per year; **P_E** is the price of energy – electricity, hydrogen or fossil fuel; **EI** is energy intensity of vehicles used; and in **$C_{O\&M}$** are included other annual- and maintenance costs; **j** type of vehicles.

The energy price is calculated as a sum of the net price P_{net}, the value-added tax (VAT) τ_{VAT}, CO_2 based tax τ_{CO2} and an excise tax on fuels τ_{Excise}:

$$P_{E_j} = P_{net} + \tau_{VAT} + \tau_{CO_2} + \tau_{Excise} \quad (3)$$

The figures for O&M costs are derived from an investigation of the overall O&M costs including also the insurance costs for an average of Western European countries. They are in the similar magnitude to those used in literature [8,9].

The future development of the investment costs is calculated considering possible technological learning for all analysed vehicle technologies according to the equation:

$$IC_j(x_t) = IC_j(x_{t_0}) \cdot \left(\frac{x_t}{x_{t_0}}\right)^{-b} \quad (4)$$

Where **IC_j** is the investment cost at time t and t_0; **x** is the cumulative number of vehicles at times t and to, and **b** is the learning index.

Starting from the historical market development of vehicles stock, future quantities are determined by extrapolating existing trends up to 2050.

In our model investment costs are divided into costs that reflects costs of mature technology components IC_{Con} and costs of new technology components IC_{New} e.g. battery and fuel cells:

$$IC_j(x_t) = IC_{Con}(x_t) + IC_{New}(x_t) \quad (5)$$

4.2 Environmental assessment

The CO_2 emissions per vehicle category are calculated considering Well-to-Tank (WTT), Tank-to-Wheel (TTW) and lifecycle car (LCA-Car) emissions, see Figure 8. WTT block includes emissions related to the upstream process related to fuel production (e.g. electricity, hydrogen) and distribution. These emissions depend on the primary energy sources used for electricity generation and hydrogen production, as well as on the energy conversion technology used (e.g. hydrogen production by electrolysis or steam reforming). TTW block covers all emissions generated during vehicle operation. In addition to these Well-to-Wheel (WTW) emissions, in LCA-Car block, vehicle cycle emissions are included. The vehicle cycle includes all emissions related to the vehicle manufacturing (including battery and fuel cell), as well as vehicle disposal.

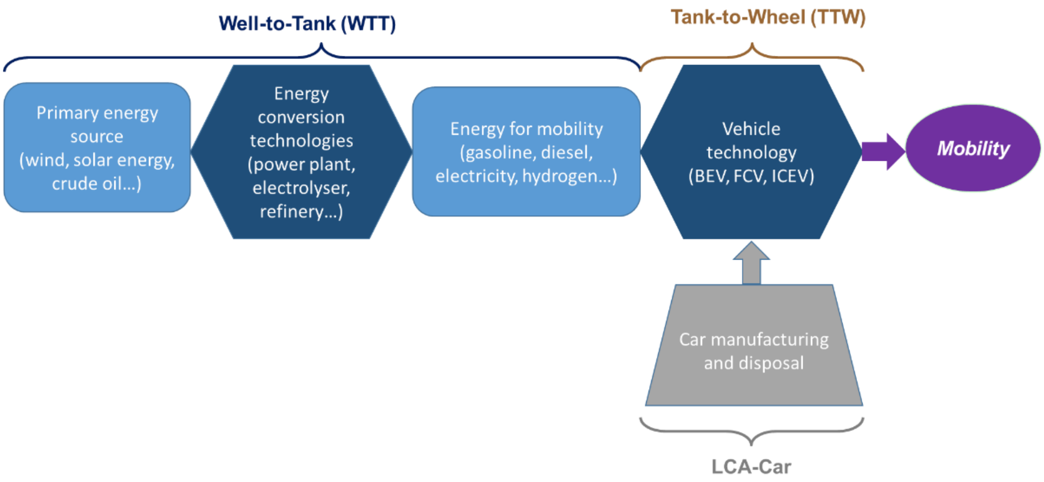

Figure 8. Mobility: The method of emission assessment.

The total CO_2 emissions, including WTT, TTW as well as emissions from car manufacturing and disposal (LCA-Car), caused by different type of vehicles and fuels are calculated using following equation:

$$CO_{2\_total} = CO_{2\_WTT\_Energy} + CO_{2\_TTW\_Energy} + CO_{2\_LCA\_Car} \quad (6)$$

Where $\mathbf{CO_{2\_WTT\_Energy}}$ are emissions by production and supply of energy used for mobility *e.g.* gasoline, diesel, electricity, hydrogen. These also include electricity generation and distribution, hydrogen storage and distribution in their system boundary; $\mathbf{CO_{2\_TTW\_Energy}}$ are emissions caused during vehicle use; and $\mathbf{CO_{2\_LCA\_Car}}$ are emissions caused by car manufacturing and disposal.

For environmental analyses, we have mainly relied on the literature [71–73]. For 2020 we use the carbon intensity of electricity mix of 240 gCO_2/kWh representing the average EU-Mix over the years 2018–2020 to avoid the full impact of COVID in 2020 based on the IEA statistics [74]. To show the impact of electricity mix on total emissions, two scenarios are used. In an optimistic scenario (RES), it is assumed that electricity is produced only from renewable energy sources, and in a conservative scenario (EU-Mix), future development of the carbon intensity of electricity mix is based on numbers reported by the IEA [75], resulting in 120 gCO_2/kWh in 2050. A similar scenario is used by Bubeck et al [8] who ends up with less optimistic figures for carbon intensity of electricity, about 180 gCO_2/kWh. The corresponding numbers for WTT, TTW and LCA_Car emissions for 2020 as well as 2050 are documented in Tables A3 and A4 in the Annex.

5. Results

5.1 Economic analysis

In the following, the results of the economic analysis are presented for the years 2020 and 2050. Figure 9 shows the structure of total costs of mobility for different types of vehicle technologies in 2020 assuming a driving distance of 15000 kilometres per year. It can be seen that the main problem of BEV and FCV are the higher capital costs. The major reasons for this are the high costs of batteries and fuel cells.

With respect to the future development of the investment costs of alternative powertrains, it is expected that they will decline due to technological learning. Technological learning is usually illustrated by so-called experience or learning curves. The learning curve describes "the fractional reduction in cost for each doubling of cumulative production or capacity" [76]. For BEVs as well as for FCVs in this paper, learning rates of 15% are applied [76,77]. In fact, this learning rate is applied to the “new” car components such as batteries and fuel cells, which have potential for the technological learning. For the mature car components *e.g.* glider, no technological learning is expected in the future as well as in the case of the conventional vehicles. Some possible improvements in conventional cars are usually compensated with additionally provided services.

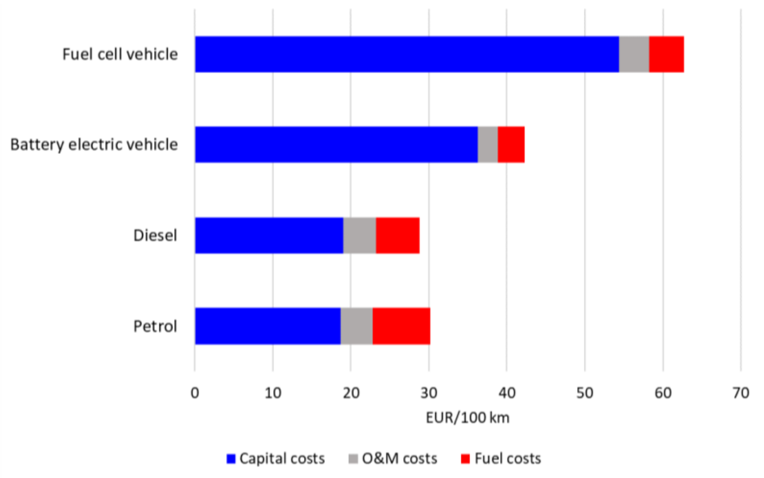

Figure 9. Total costs of ownership of passenger cars per 100 km driven in 2020 (Average car capacity: 80 kW, driving range for all cars 15000 km/year).

The total costs of ownership of different types of passenger cars per 100 km driven in the year 2050 are depicted in Figure 10. It can be seen that the specific capital costs will remain the cost component with the highest impact on the total cost for all vehicle technologies investigated. However, by 2050 total mobility costs of the cars analysed will almost even out, see Figure 11. BEV may even become the cheapest option, mainly because of its low energy costs. For diesel and petrol cars fuel costs will become higher mainly due to increasing CO_2 taxes.

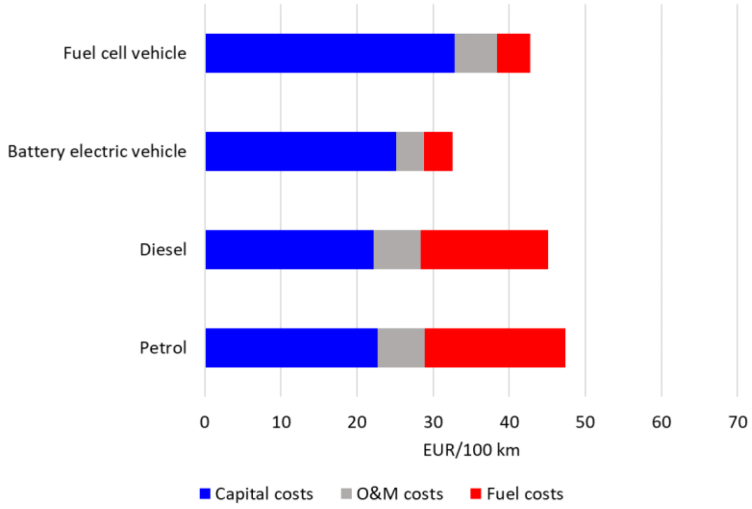

Figure 10. Total costs of ownership of passenger cars per 100 km driven in 2050 (Average car capacity: 80 kW, driving range for all cars 15000 km/year).

5.2 Environmental analysis

Figure 12 provides a comparative environmental assessment of different passenger car technologies, documenting WTT-, TTW- and the embedded CO_2 emissions of cars related to the materials and assembly of vehicles. Moreover, the combinations of different energy sources used in electricity and hydrogen production are considered. For electricity generation, two cases are analysed: (i) electricity production using an average European energy mix (EU-Mix) with carbon intensity of 240 gCO_2/kWh, (ii) and electricity production using only renewable energy sources (RES) with 12 gCO_2/kWh. In addition, two possibilities for hydrogen production are considered: (i) hydrogen production by the steam reforming of natural gas (NG-EU-Mix), and (ii) hydrogen production by electrolysis with electricity from RES. As shown in Figure 12, the primary energy sources used for electricity and hydrogen production have a huge impact on the total CO_2 emissions per kilometre driven. It is also important to note that BEVs and FCVs do not cause emissions at the point of use unlike conventional vehicles, which makes their use very attractive in polluted urban areas. The major finding of Figure 11 is that BEVs as well FCVs are clearly preferable to conventional cars from an environmental point of view, but if electricity and hydrogen are produced from RES the additional saving effect is about 50%.

Technical progress in car manufacturing and assembly, as well as in the provision of materials used, especially for batteries, fuel cells and hydrogen tanks, can be expected in the future [48]. Such development could reduce embedded car emissions, which could be about

10% lower for the car and about 20% lower for the battery and the fuel cell than in 2020, see *e.g.* Bieker [73], who reports similar numbers up to 2030.

A comparative environmental assessment of CO_2 emissions of vehicle technologies analysed is shown in Figure 12, including WTT-, TTW- and the embedded CO_2 emissions for 2050. Regarding WTT- and TTW figures, it is important to state that increasing energy efficiency and lower fuel intensities are expected for all types of cars [78,79]. The major assumptions for the fuel intensities in 2050 are documented in the Annex. It is assumed that they will be at least for about 30% lower than in 2020 for all car types [80,81]. The major result of Figure 12 is that BEVs as well FCVs are still preferable to conventional cars but it is important to strive for further increases in the electricity and hydrogen production from RES.

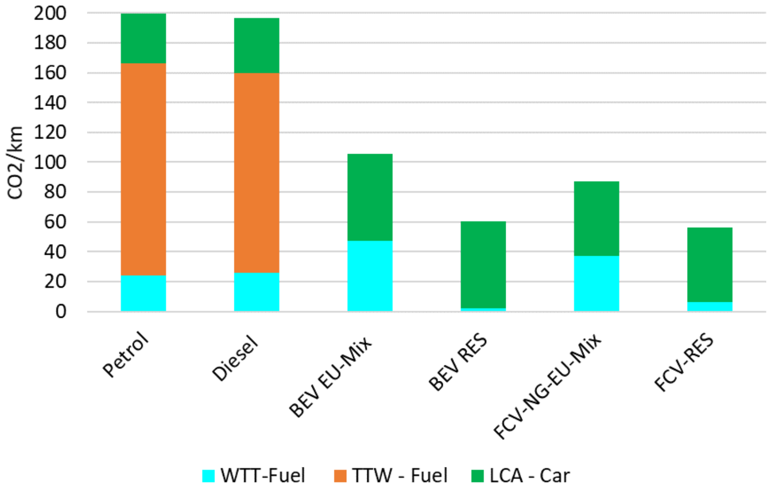

Figure 11. WTT-, TTW- and embedded car CO_2 emissions of conventional and alternative vehicles and various energy sources in 2020 (Car size: 80 kW, driving range for all cars 15000 km/year).

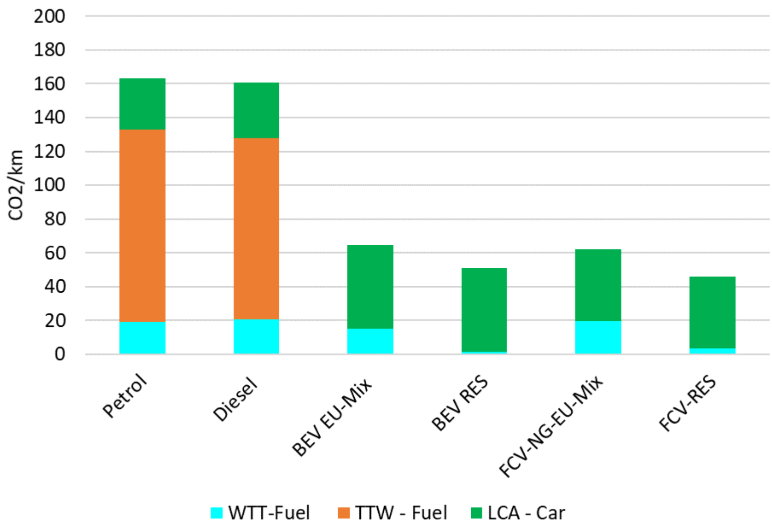

Figure 12. WTT-, TTW- and embedded car CO_2 emissions of conventional and alternative vehicles and various energy sources in 2050 (Car size: 80 kW, driving range for all cars 15000 km/year).

5.3 Sensitivity analysis

To show the impact of the most important parameters on the total mobility costs and emissions a sensitivity analysis is conducted. Besides our "base case" which is calculated assuming yearly driving range of 15000 km and vehicle depreciation time of 8 years, three additional cases are analysed: (i) case with longer depreciation time (12 years), (ii) case with shorter driving range per year (11000 km), and (iii) case with higher electricity prices (80 ct/kwh) assuming electric vehicle charging at rapid charging stations. All these cases are shown in Figure 13.

It is clear to see that longer depreciation time could reduce total costs per km driven for all car categories because of lower capital cost per km driven. In opposite, shorter total driving range per year leads to an increase of the total costs. In the case that battery electric vehicles are not charged at home but at fast charging stations, they are much less competitive with conventional cars and have the highest energy costs.

Currently, in all analysed cases battery, electric and fuel cell vehicles are not competitive with conventional cars. However, in the future this can be changed. Figure 14 shows a sensitivity analysis for the year 2050. Due to the reduced capital costs, total mobility costs are more sensitive on the changes in the number of km driven per year, depreciation time and energy prices. Except in the case of rapid charging, BEVs have the lowest total costs. In general, by 2050 the TCO in all cases analysed are in a much closer range then today.

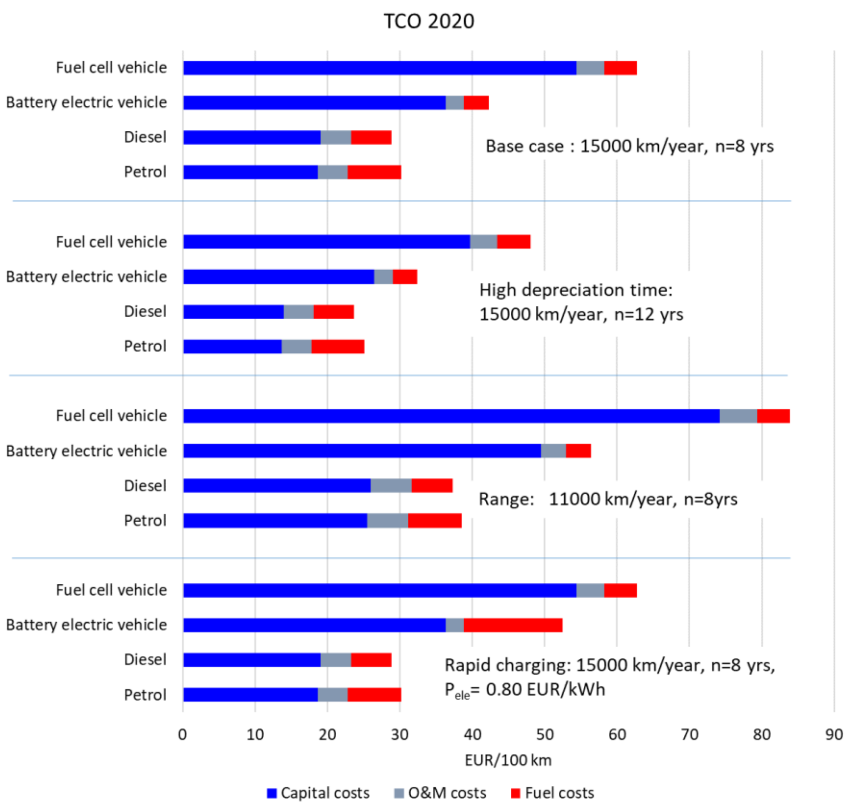

Figure 13. Sensitivity analysis of total costs of ownership of passenger cars in 2020 for selected cases.

The changes in parameters discussed here have also an impact on the total CO_2 emissions, however, the highest impact on the total emission has energy mix used for electricity generation and hydrogen production as shown in Figure 11 and Figure 12 for an average EU electricity mix (case: EU-Mix) and for a case where only renewable energy is used (case: RES). In the future, also the EU energy mix will become greener leading to higher environmental benefits of electric vehicles.

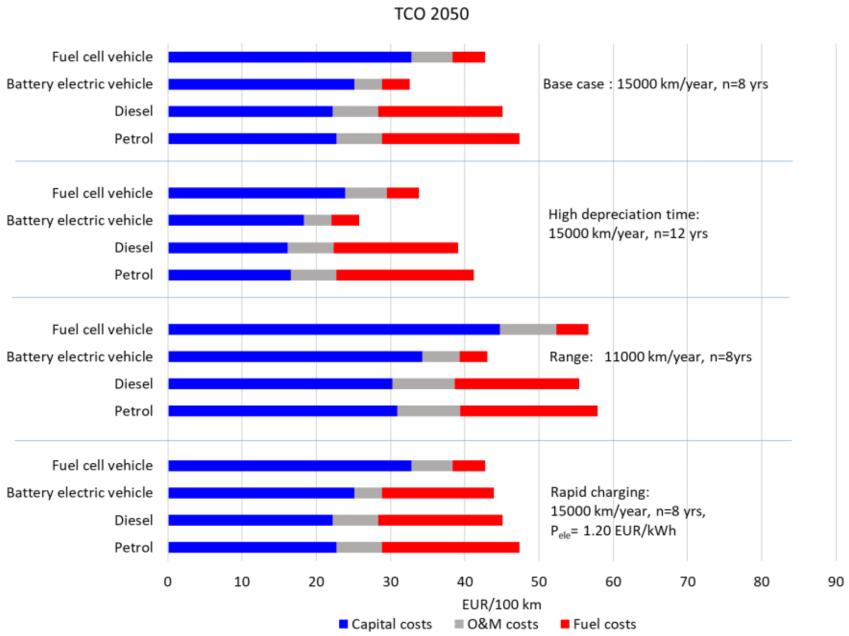

Figure 14. Sensitivity analysis of total costs of ownership of passenger cars in 2050 for selected cases.

6. Conclusions

Despite the currently unfavourable economics and lack of infrastructure, BEVs and FCVs could provide contributions to the decarbonization of road transport in the mid-term. The major conclusions are:

Regarding the environmental benignness of BEVs and FCVs, two issues are very important: (i) the carbon emissions in the WTW chain depend very strongly on the energy sources used for the production of electricity and hydrogen. In many countries, even today, coal is a major source for electricity generation and in such a case EVs do not contribute to reduction in over-all carbon emissions. Hence, electricity and hydrogen for EVs should be certifiably produced from renewable energy sources. (ii) Moreover, with the increasing use of EV, it is becoming more and more important to ensure fairness and environmental sustainability through the whole mobility supply chain, from raw material mining up to disposal and recycling of vehicles.

How soon EVs will contribute to emission reduction is very dependent on the development of their economic performance. The investment costs of EVs have been decreasing over the last decades and they could become fully competitive on the market with the proper policy support during their early market stage. However, the major remaining uncertainty regarding the investment costs of BEVs and FCVs is how fast technological learning takes place, especially regarding the battery and fuel cells. Since currently about 80% of all electric car charging takes place at home [88], what is usually cheapest way to go considering average household electricity prices in the EU, energy costs of BEVs are already competitive today with conventional fuels and other O&M costs do not play an important role.

Finally, we conclude that the future relevance of BEVs and FCVs is highly dependent on the policies implemented. In the short-term, subsidies for BEVs and FCVs might still be an incentive but with the increasing number of EVs they will be abolished as well as all non-monetary measures. In the long run, policies should be oriented on the CO_2 emission reduction benefits and on the "damage" the vehicles cause. Moreover, intended bans on diesel and petrol vehicles in some countries (*e.g.* in Norway starting from 2025) will accelerate the use of electric vehicles.

However, despite the fact that there may be significant progress regarding these alternative automotive technologies, they will not solve the major problems. It is obvious that also other strategies are necessary to head towards a sustainable transport sector.

In addition to technical solution the implementation of the "Avoid-Shift-Improve" strategy is needed, see Figure 15. The major goals of this strategy are:

- to avoid unnecessary travel and reduce trip distances
- to shift to more energy efficient and sustainable transport modes
- to improve the energy efficiency of vehicles as well as transport practices.

The success of this strategy is dependent on the policy framework provided, which should contribute to the reduction of commuting, better conditions for non-motorized transport, better quality of public transport, as well as a better integration of transport in urban and spatial planning.

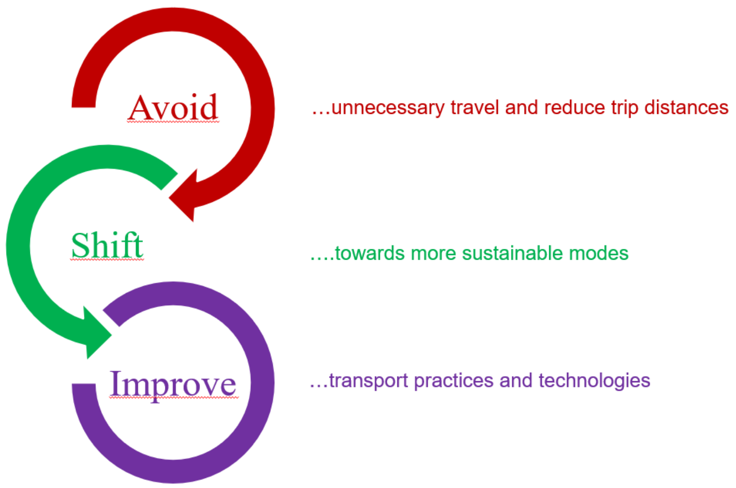

Figure 15. Avoid-Shift-Improve strategy.

Authors' contribution

A.A.: conceptualization, methodology, analysis, writing (original draft). R.H.: methodology, analysis, writing (review).

Conflicts of Interests

We have no conflicts of interest to disclose.

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Appendix

In the following tables the major input data for the calculation and scenarios derived are documented based on the major statistical input data [83-87].

Table A-1. The main data used for the economic assessment, 2020.

2020	**Investment costs (incl. 20% VAT)**	**O&M costs**	**Distance driven**	**Fuel price (incl. tax)**	
	EUR/car	EUR/car/yr	km/car/yr	EUR/unit	Unit
Petrol ICE	18106	624	15000	1.43	€/l petrol
Diesel ICE	18484	624	15000	1.10	€/l diesel
BEV	35201	382	15000	0.20	€/kWh
FCV	52728	573	15000	8.88	€/kg H2

Table A-2. The main data used for the economic assessment, 2050.

2050	**Investment costs (incl. 20% VAT)**	**O&M costs**	**Distance driven**	**Fuel price (incl. tax)**	
	EUR/car	EUR/car/yr	km/car/yr	EUR/unit	Unit
Petrol ICE	21998	929	13000	3.84	€/l petrol
Diesel ICE	21490	929	13000	4.11	€/l diesel
BEV	24344	557	13000	0.30	€/kWh
FCV	31793	836	13000	7.37	€/kg H2

Table A-3. The main data used for environmental assessment, 2020.

2020	**Embedded emissions of car**	**CO_2 Fuel intensity**	**WTT-Fuel**	**TTW-Fuel**
	ton CO_2/car	kWh/100km	g CO_2/MJ	g CO_2/MJ
Petrol	6.0	46.1	12.5	73.4
Diesel	6.6	50.8	14.2	73.3
BEV EU-Mix	10.5	17.0	66.7	0.0
BEV EU-RES	10.5	17.0	3.3	0.0
FCV-H2 NG	9.0	26.8	33.0	0.0
FCV-H2 RES	9.0	26.8	5.6	0.0

Table A-4. The main data used for environmental assessment, 2050

2050	**Embedded CO_2 emissions of car** *ton CO_2/car*	**Fuel intensity** *kWh/100km*	**WTT-Fuel** *g CO_2/MJ*	**TTW-Fuel** *g CO_2/MJ*
Petrol	5.4	35.2	12.5	73.4
Diesel	5.9	32.4	14.2	73.3
BEV EU-Mix	8.9	12.6	33.3	0.0
BEV EU-RES	8.9	12.6	2.8	0
FCV-H2 NG	7.7	19.8	27.8	0.0
FCV-H2 RES	7.7	19.8	5.0	0.0