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Economic and Environmental Prospects for Battery Electric- and Fuel Cell Vehicles: A Review▲

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Abstract

Due to the pressing environmental problems coming from the transport sector, interest in electric vehicles (EVs) has increased significantly over the last decade. Although different types of EVs are available on the market, the largest contribution to the reduction of environmental problems could be made through zero-emission vehicles, such as battery electric vehicles (BEVs) and fuel cell vehicles (FCVs). Each of these vehicles has some advantages and disadvantages. The problem they share is the high purchase price in comparison to conventional gasoline vehicles. Through the improvement of battery performance, further technological learning and a mix of different direct and indirect supporting policy measures, the competiveness of EVs could be significantly improved. EVs could already contribute to the reduction of emissions today, however the full environmental benefit of BEVs and FCVs is related to the mix of the primary energy sources used for electricity generation and hydrogen production. The increasing use of renewable energy sources in electricity generation makes EVs more environmentally friendly. Since total emissions are also dependent on the embedded emissions of cars, their lifetime as well as their usage (specific vehicle kilometers driven per year) have significant impacts on the total emissions per km driven.

Keywords: Alternative Fuels, Efficiency, Environmental Impact, Hydrogen Car, Well-to-Wheel

1 Introduction

Worldwide the transport sector accounts for about 27% of the final energy consumption. Since transport is the least diversified energy sector relying almost completely on fossil fuels, it causes about 25% of the world carbon dioxide emissions [1, 2]. The largest amount of the total transport greenhouse gas (GHG) emissions comes from road transport, especially from passenger cars. Despite the policies and measures implemented worldwide with the goal of reducing energy consumption and GHG emissions from the transport sector, car ownership and road traffic are continuously increasing.

In Europe, the transport sector is responsible for about 33% of total energy consumption, and causes about a quarter of total GHG emissions. Road transport is the biggest emissions-emitter accounting for more than 70% of all GHG emissions from transport [3]. The largest percentage of these emissions, 61%, is caused by cars, see Figure 1. The broad portfolio of policies and measures implemented so far has stopped the increase in emissions in almost all energy sectors, but not in the transport sector.

However, the future goals of European policy are mainly directed toward reduction of the GHG emissions and increasing use of renewable energy sources (RES). According to the EU regulation (No 333/2014) the goal is to reduce the CO_2 emissions of new passenger cars. The target for the end of 2020 is 95 g CO_2 per km. Since internal combustion engine (ICE) vehicles are already a mature technology, significant improvements cannot be expected. To achieve this target it will be necessary to increase the use of alternative automotive technologies, such as electric vehicles.

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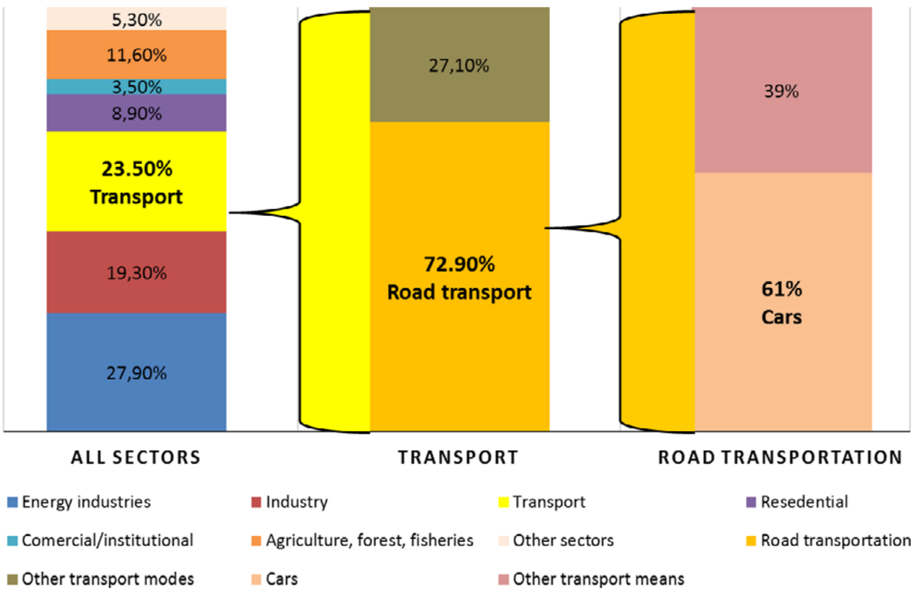

Fig. 1 GHG emissions in the EU 28 (i) by sector, (ii) from transport by mode, and (iii) from road transport by transport mean, 2015 [4].

dominant. Over the last few years the electrification of the transport sector has often been discussed and promoted. However, looking at the facts, it can be noticed that only about 1.7% of global electricity consumption was used for transport in 2016 (the share in 1975 was even higher 2.4%). Figure 2 shows electricity use by sector.

Nevertheless, due to growing and increasingly-evident environmental problems, the situation could change in the future. The use of passenger ICE vehicles powered by fossil fuels is becoming progressively complicated due to different restrictions, such as the rising number of zero emission zones. Recently, some countries have even decided to stop the registration of diesel cars [11]. At the same time, with the increasing use of RES, the interest in EVs is growing. They have been recognized as possible contributors to a more sustainable development in the transport sector.

The European climate and energy package for 2020 (so called 20-20-20 package) sets four key targets: (i) to reduce GHG emissions by 20% by 2020 taking the 1990 emissions as the reference, (ii) to improve energy efficiency by 20%, (iii) to reach 20% of renewable energy in the total energy consumption in the EU by 2020, and (iv) to reach 10% of renewables in the total energy consumption of vehicles by 2020 [5]. The 2030 climate and energy framework (40-27-27) sets further targets in view of GHG emission reduction, increasing the use of renewables, and efficiency improvements for the year 2030 [6].

According to the White Paper on Transport, key goals to be reached by 2050 include halving the use of conventional fossil fuels cars in urban transport by 2030, and to phase them out in cities by 2050 [7].

All of these targets make alternative automotive technologies more attractive. In the future, so-called zero-emission vehicles which can be used in zero emissions zones (ZEZ) will be of special interest. The number of cities planning to introduce ZEZ is increasing (e.g., London, Amsterdam, Copenhagen, Oxford, Stockholm, Oslo, Bergen, Madrid, etc.) [8].

In addition, the European "low-emission mobility strategy" adopted in July 2016 is in line with previous targets. The main elements of this strategy are (i) increasing the efficiency of the transport system using digital technologies, smart pricing and promoting the shift to lower emission transport modes, (ii) speeding up the deployment of low-emission alternative energy for transport, such as advanced biofuels, electricity, hydrogen and renewable synthetic fuels, and (iii) moving towards zero-emission vehicles [9].

Despite all of the policies and measures implemented worldwide over the last years with strong support given to more environmentally-friendly transport technologies and modes, conventional ICE vehicles and fossil fuels are still pre-

Over the last few years, different aspects of EVs have been analyzed in literature. Due to the rising environmental problems, a wide range of papers focus on the environmental issues of EVs. However, these analyses often focus on some specific regions or car types. For example, Anair and Mahmassini [12] analyzed the emissions of EVs in several electricity grid regions in the USA. Kamiya et al. [13] explored the well-to-wheels GHG intensity of PEVs in three regions with very different electricity grid profiles: the Canadian provinces of British Columbia, Alberta, and Ontario. Ma et al. [14] provides a comparison of the total GHG emissions of BEVs in comparison to conventional vehicles. Most of the papers have stressed that the full environmental benefits of EVs can be reached only in combination with electricity from RES (e.g., [15–17]). However, the major problem is that it is very difficult to make a comparison between studies. As documented by Hawkins et al. [18], which has reviewed about 50 studies on the lifecycle of EVs, studies have different definitions of life cycle assessment (LCA) boundaries, scopes and methods.

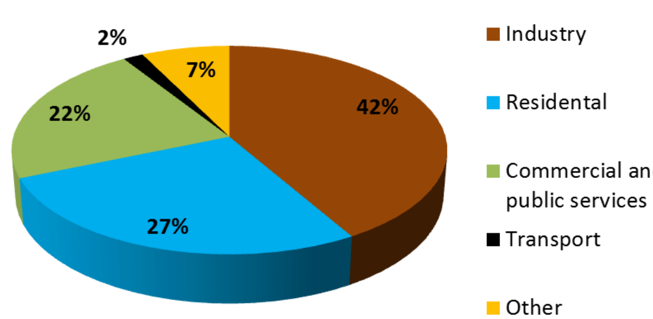

Fig. 2 Electricity use by sector [10].

The economic assessment of EVs is mostly conducted by using the total cost of ownership (TCO) approach. The majority of previously published papers considered vehicle ownership costs in just one country or one geographic region (e.g., Gilmore and Patwardhan [19] consider passenger vehicle TCO in India, and Diao et al. [20] look at private car TCO in China). Palmer et al. [21] provide an extensive assessment of the TCO of conventional, hybrid, plug-in hybrid and battery electric vehicles in three industrialized countries (UK, USA-using California and Texas as case studies, and Japan) for time period 1997–2015, stressing the importance of financial subsidies for EVs, as well as non-financial incentives. Moreover, this paper provides a review of five studies on TCO, showing the major differences in assumptions. Riffini and Wei [22] provide a detailed life cycle cost analysis for FCV in comparison to other vehicle technologies. The future costs of FCVs in California are calculated using a learning rate approach. Their results show that the fuel cell system is the key factor in making FCVs competitive with conventional cars. So far, most of the studies on hydrogen and FCVs have focused on the case of California [23–26], a leading region in terms of the use of FCVs and the development of hydrogen infrastructure [27].

However, assumptions regarding car-size and lifetime of vehicles, as well as battery, are very different from study to study. In addition to this, the economic assessment of EVs is especially sensitive regarding assumptions related to the specific number of km driven per year which also differ in literature (see Section 5). This makes a detailed comparison between studies very difficult.

This paper builds on previous research, synthesizing and updating our previous work and providing a holistic review focusing on zero-emission vehicles including:

(i) a comparative analysis of BEVs, FCVs and ICE vehicles;
(ii) a dynamic scenario analysis;
(iii) a sensitivity analysis;
(iv) a simultaneous consideration of economic and environmental aspects.

In detail the core objective is to provide a comprehensive review of the most important issues related to the economic and environmental assessment of battery electric and fuel cell vehicles in comparison to conventional gasoline ICE vehicles. The economic analysis is based on the widely used total cost of ownership methodology. In addition, we conduct an economic sensitivity analysis with respect to the impact of the specific kilometers driven, depreciation time, interest rates, as well as other operating and maintenance costs. Regarding the future prospects of battery electric vehicles and fuel cell vehicles from an economic point of view, we use the technological learning approach and derive scenarios for up to 2050. For the environmental assessment of the technologies analyzed, CO_2 emissions from the whole energy supply chain are considered.

This paper is divided into 7 sections. In the next section, we briefly present some details on the history of BEVs and FCVs. Subsequently, we discuss hydrogen and electricity production. This is followed by the documentation of the different types of EVs and their development. In Section 5 we present a comprehensive literature overview related to the total costs of ownership and provide our own cost analysis of the mobility with BEVs and FCVs. An environmental assessment of BEVs and FCVs in comparison to conventional ICE vehicles is provided in Section 6. Conclusions complete this paper.

2 History

The discussion on what will be the automotive technology of the future has been already ongoing for many years and even seems to intensify recently. Over the years, there have been many hypes regarding most likely technology and fuel enabling sustainable development of the transport sector. The first increasing popularity of EVs was in period 1890–1920, but followed by a decline in the 1920s due to several technical and economic factors. The first wave of the revival in EVs sales started in the early 1970s due to the first oil crisis [28]. For the first time fuel cell passenger cars have been tested in demonstration projects in the 1960s [1]. In the 1990s the interest in FCVs was boosting again [1], and in the early 2000s, public attention on FCV and hydrogen peaked [29]. Some years later, electricity and EVs have been seen as a way to sustainable mobility. Due to slow market penetration of EVs and moderate technical improvements of batteries, around 2007 came biofuels hype. However, very soon, some problems related to biofuels use, such as modest emission-reductions and competition between food and fuel production have been recognized [28, 30]. In the meantime, at the beginning of the 21st century, EVs came on the stage again, this time with the new type of battery – lithium-ion battery. Major steps in the development of EVs and hydrogen are given in Figure 3.

Although the technological developments in the transport sector have been spread in different directions, the major goals is the same – to decrease energy use in the transport sector and corresponding local pollutions and GHG emissions, as well as to increase energy supply security. To be successful and acceptable, all alternative mobility solutions should be competitive with conventional cars regarding costs and performances (e.g., driving range, comfort, charging time, etc.) or provide some significant benefits for car users and environment.

3 Hydrogen *vs.* Electricity

Electricity and hydrogen have been often discussed as clean energy carriers for sustainable mobility. They are complementary energy carriers, both secondary energy carriers, which can be used to provide different energy services in a very broad range of applications in all energy sectors – the transport-, power-, industry-, and building sector. However, dependent on primary energy used for their production, selected production methods and energy supply chains[1], they

[1] *Note that very long and complicated supply chains could have very low energy efficiency due to losses at every conversion step.*

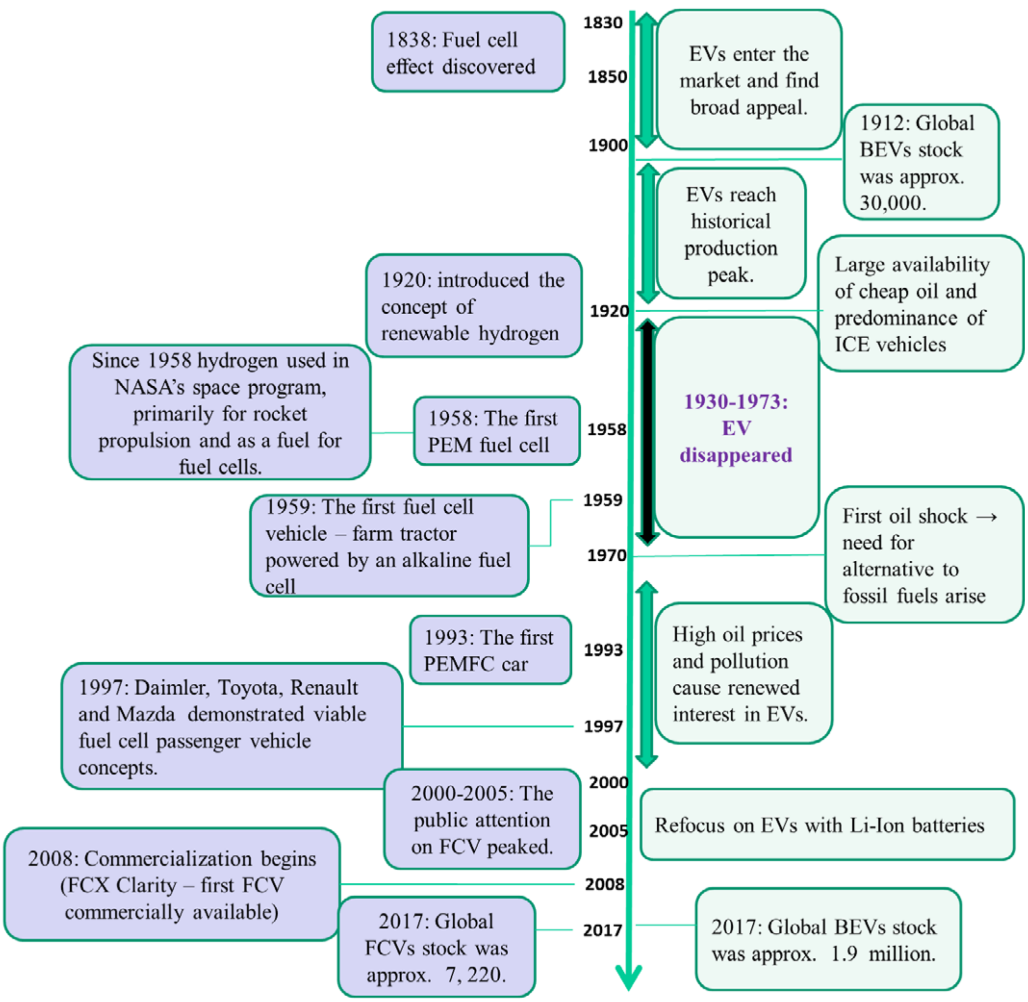

Fig. 3 Major steps in the development of BEVs and FCVs.

could have very different costs as well as associated GHG emissions.

3.1 Electricity Generation

In 2016, total net electricity generation in the EU-28 was about 3.10 million GWh. Almost a half (48.7%) of the electricity generated came from fossil fuels (such as natural gas, coal and oil) and about one quarter (25.7%) came from nuclear power stations. Among the renewable energy sources shown in Figure 4, the highest share of net electricity generation in 2016 was from hydropower plants (12.1%), followed by wind turbines (9.7%) and solar power (3.5%) [32].

Due to existing policy framework in the EU (e.g., Energy and Climate Change Packages for 2020 and 2030) amount of renewable energy sources in electricity generation is continuously increasing. The mix of primary energy sources used for electricity generation has huge impact on the total carbon

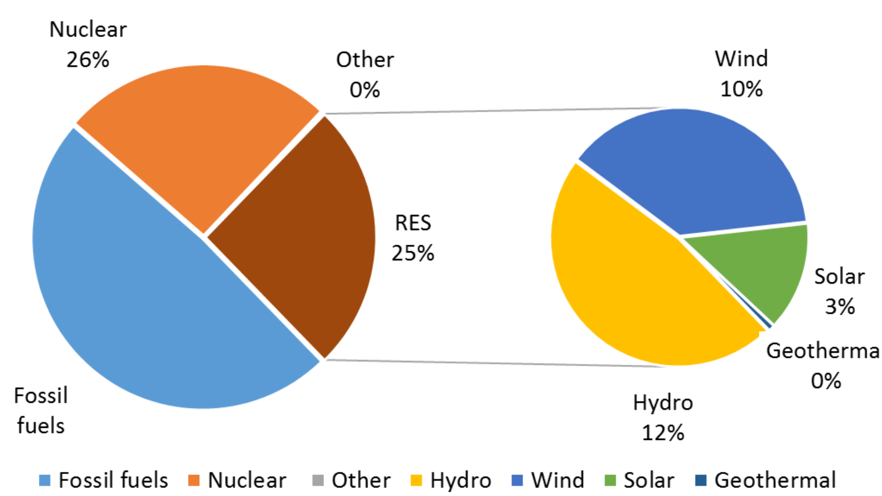

Fig. 4 Net electricity generation in EU 28, 2016 [32].

intensity of grid electricity. Due to different primary sources used for electricity generation as well as different electricity losses in transmission and distribution, total carbon intensity is very different from country to country. The carbon intensity of the electricity mix in European countries is shown in Figure 5.

Increasing use of renewable energy in electricity generation is one of the priorities of the European energy and climate policy. Indirectly, this makes EVs more environmentally friendly and consequently more attractive.

3.2 Hydrogen Production

Since hydrogen cannot be found free in nature, it has to be extracted from different energy sources. Worldwide, about 50 million metric tons of hydrogen are produced annually [33–35]. Although, hydrogen can be produced from various energy sources using different methods, it is currently predominantly made from fossil fuels by steam reforming of natural gas, see Figure 6.

Electrolysis from electricity currently accounts for about 5% of total hydrogen production. Major reason for this is significantly higher hydrogen production costs in comparison to steam reforming of natural gas [1,36]. Since economic attractiveness of hydrogen production by electrolysis is very dependent on electricity prices, one possibility to reduce hydrogen production costs, as well as to increase environmental benefits of hydrogen, is to use surplus renewable electricity in electrolysers [34]. However, the use of renewable energy in hydrogen production is currently very low. Yet, with the pressing environmental problems and increasing use of volatile RES in electricity generation, this could be changed in the future.

Since hydrogen can be produced from different primary energy sources using different production methods and scale,

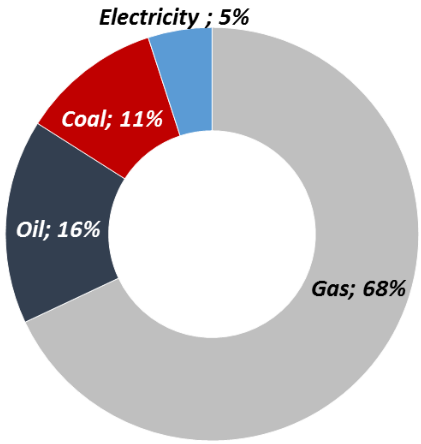

Fig. 6 Global hydrogen production [1].

total costs could be very different. As an example, range of the hydrogen production costs with steam reforming and electrolysis are shown in Figure 7.

4 Battery Electric- and Fuel Cell Vehicles

Electric vehicles have been recognized as more environmentally technology, with which local air pollution and global GHG emission can be reduced. The use of EVs is currently largely driven by supporting policies, especially different regulatory-, financial- and non-financial measures. With effective policies and measures, EVs should become more attractive to private and public use. Higher acceptance of EVs would reduce risks for investment in E-mobility and encourage car manufactures to scale up production.

Moreover, currently implemented access restrictions for ICE vehicles, especially for diesel vehicles, make EVs more

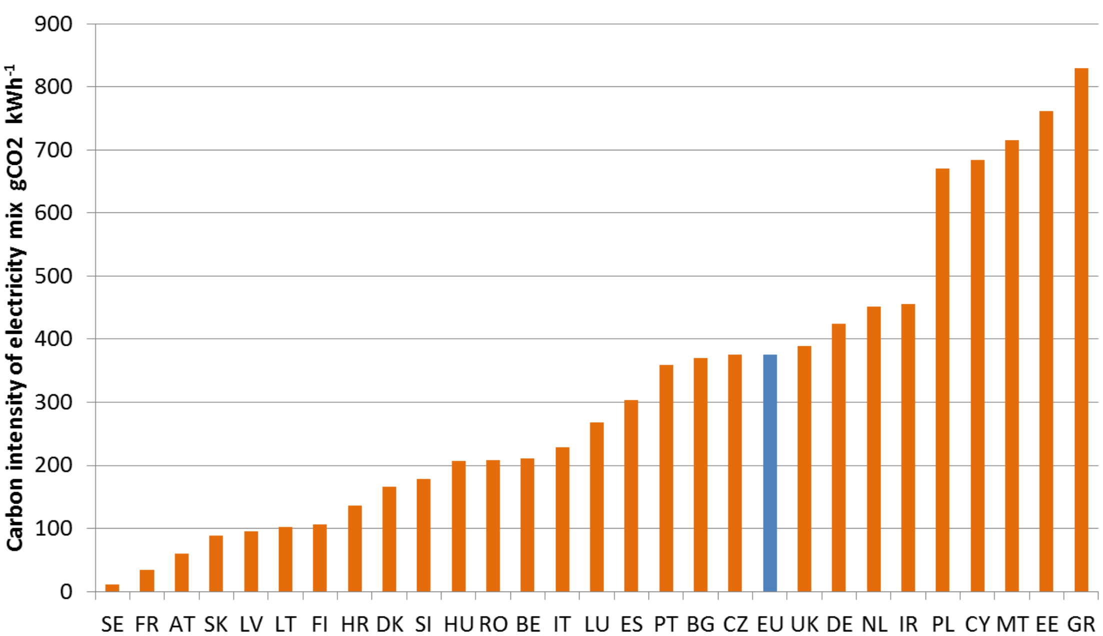

Fig. 5 Carbon intensity of the electricity mix in different European countries, 2014 (own compilation based on [31]).

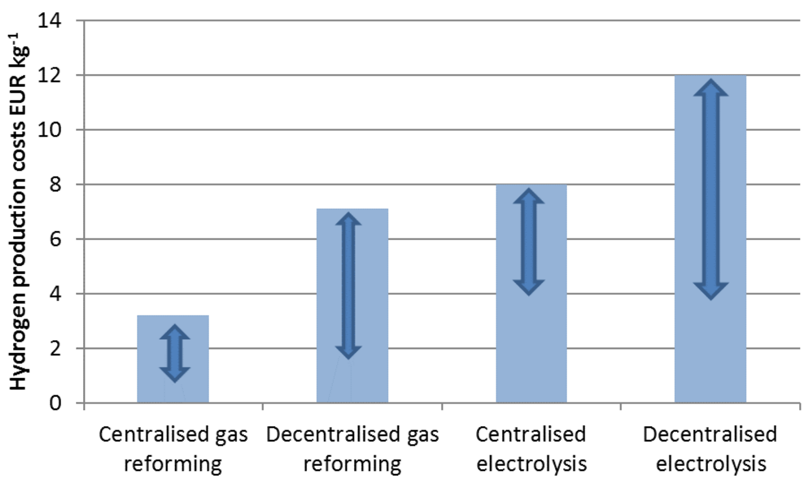

Fig. 7 Hydrogen production costs [1].

Electric vehicle stock increased rapidly over the last few years, reaching about 3.1 million passenger rechargeable electric vehicles in 2017. The largest amount of these vehicles is in the USA, Europe, and especially China, about 40%, see Figure 9. However, by far Norway has the world's highest share of electric vehicles in its vehicle stock, 6.4% [37].

In 2017, the global FCVs stock was about 7,200 [37]. The United States, especially California, accounted for about 49% of the global FCVs fleet. On the second place is Japan, with about 2,300 vehicles (about 32% of the total stock), followed by Europe with about 1,200 FCVs mostly used in Germany and France. One of the major reasons for the current very small number of FCVs used is their high cost. For example, the price of a medium-sized (C segment) FCV are around 60,000 EUR per car [1, 38]. However, it is expected that with the launch of FCV series production, their costs could be significantly lower in the future.

attractive. Several governments already announced their intention to end sales or registration of new ICE vehicles, (e.g., France, Ireland, Netherlands, Norway, etc.). In addition, many cities have implemented or are planning to implement low- or zero-emission zones, with limited or prohibit access for ICE vehicles.

There are various types of EVs which could provide different environmental benefits. Five major types of EVs – hybrid electric vehicle (HEV), plug-in hybrid electric vehicle (PHEV), range extender electric vehicle (REX), battery electric vehicle (BEV), and fuel cell vehicle (FCV) – are illustrated in Figure 8. All these vehicles have different level of electrification, and advantages and disadvantages in comparison to conventional ICE vehicles. Since HEVs are completely dependent on fossil fuels, they can be seen as more energy efficient type of ICE vehicle. For the future of interest are rechargeable EVs (PHEV, REX and BEV), especially zero-emission vehicles (BEV and FCV) which are in the focus of this paper.

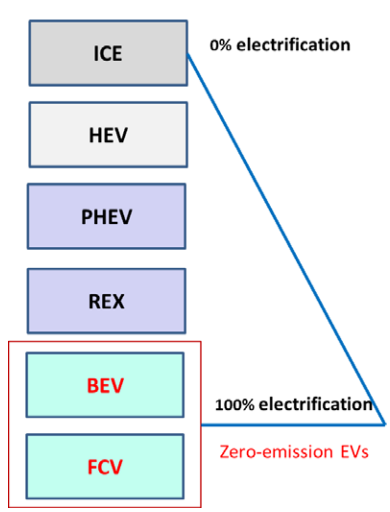

Fig. 8 Electric vehicles.

In spite of the increasing use of EVs they are still not able to compete with conventional ICE vehicles. However, there are several major reasons that can increase the attractiveness of EVs:

(i) crisis in the existing technology, e.g., increasing fossil fuels prices, problems with energy supply security, diesel emissions scandal, etc.,
(ii) supporting regulations, e.g., emission regulations;
(iii) technological/cost breakthrough for EVs;
(iv) change in behavior and preferences;
(v) availability of suitable niche markets and possibility of sector coupling;
(vi) availability of surplus electricity from RES [39, 40].

It is already obvious, that regardless of significant improvements on ICE vehicles over time, this technology faces a crisis related to its emissions. All regulations and policy measures implemented over the last years, e.g., increasing taxes on fossil fuels, emission standards, diesel bans, establishment of zero- or low-emissions zones in many urban areas, etc., have made use of ICE vehicles less attractive. On the other hand, all policies implemented as well as goals set for the future support the use of EVs directly or indirectly [5–7]. However, the future prospects of EVs are very dependent on the further development of batteries and fuel cells.

Further improvements of battery performances, especially their capacity, as well as their costs reductions are essential for the broader acceptance and use of EVs. Over time, batteries have been already substantially improved. Firstly used lead acid batteries have been replaced with lithium batteries which have much better performances. Moreover, since their market introduction in the 1990s, lithium-ion batteries have experienced significant cost reductions. However, further cost reductions are necessary to increase competiveness of EVs on the car market. Development of battery costs and their density are shown in Figure 10. In the period from 2009 to 2016 battery

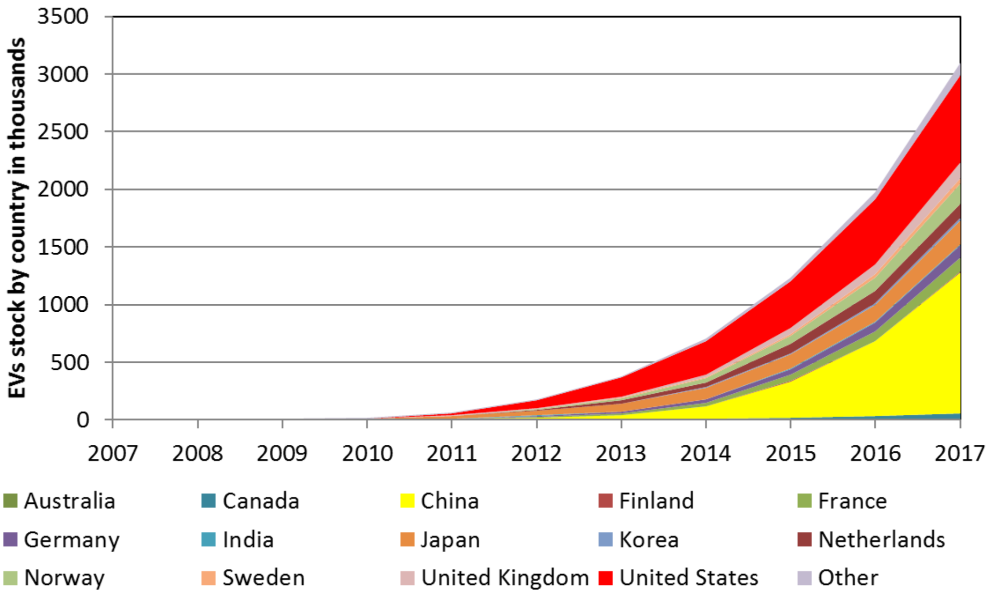

Fig. 9 Development of the global stock of rechargeable EVs [11].

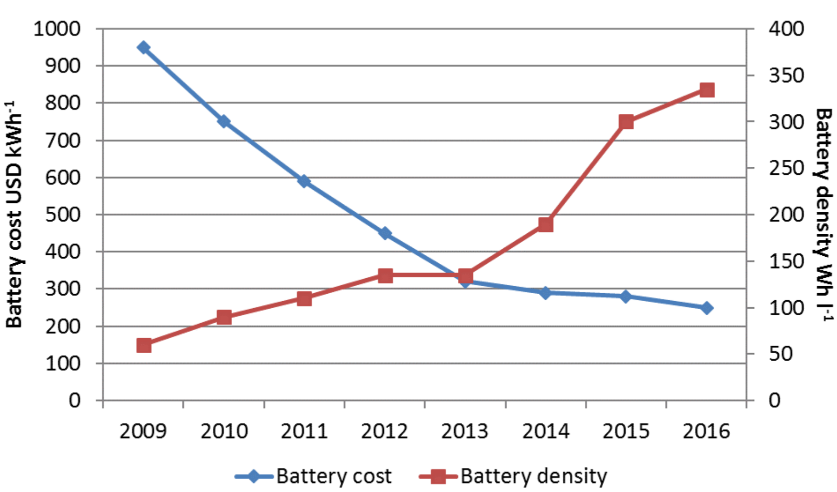

Fig. 10 Battery cost vs density [41].

costs have been reduced for about 74%. At the same time energy density has been improved more than 4 times [41]. Further cost reductions of batteries are possible due to increasing battery capacity, increasing production capacity (economies of scale), and evolvement of battery chemistries (higher energy density and lower reliance on expensive and rare materials).

Currently, almost all fuel cell passenger cars are using proton exchange membrane (PEM) fuel cell. The fuel cell stacks in the latest FCV-models have an output of 100 kW or more enabling a driving range of around 400–500 kilometers. Corresponding storage capacity is between 4 and 7 kg of hydrogen stored in pressure tanks at 700 bar [1]. In spite of good performances of FCVs, they are still not attractive to many car users due to their high costs in comparison to conventional ICE vehicles, as well as other types of electric vehicles. Major reason for their high costs is price of fuel cell system. As shown in Figure 11, fuel cell system is responsible for 50% of the total cost of FCVs.

However, according to IEA [42], fuel cell system costs should be significantly reduced in the future. In 2030 price could be slightly above 50 USD per kW, and in 2050 already below 50 USD per kW.

Moreover, in the future, ICE vehicles powered by fossil fuels will be more expensive mostly due to more complex and strict emission control systems. Then again,

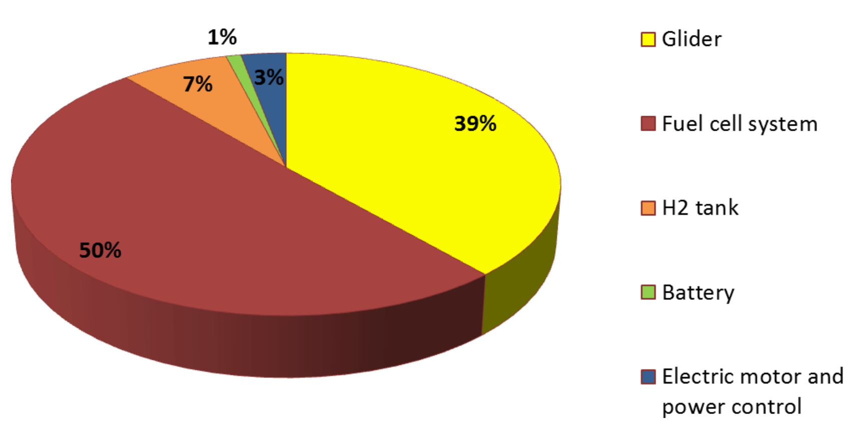

Fig. 11 Fuel cell vehicles: Structure of investment costs [42].

FCVs could become cheaper due to further developments, technological learning and scale effects. Moreover, because of advantages in terms of driving range and charging time in comparison to BEVs, FCVs could become an attractive alternative in the future. As zero-emission vehicles, FCVs are currently the only relevant alternative to BEVs.

5 The Costs of Electric Vehicles

There are few major reasons for the slow diffusion of electric vehicles. Some of them are limited driving range, long charging time, and restricted refueling infrastructure. However, one of the major reasons for the low deployment of EVs is corresponding high price of mobility.

To make EVs more attractive, policymakers have provided different kind of monetary measures in many countries such as subsidies to lower upfront costs or tax reductions and exceptions. Especially, buyers in smaller-car segments are price sensitive, and this is where many of today's EVs are being marketed [43, 44]. For increasing use of EVs, they have to be competitive with conventional ICE vehicles on price, as well as on performance.

The economic comparison between different kinds of EVs and conventional ICE vehicles is usually based on the calculation of the total cost of ownership [45–48]. The calculation of the total cost of ownership includes not just the car purchase price but all related ownership costs such as insurance, registration, maintenance costs, repairs costs, energy costs, etc. A level of the details included in the calculation of the TCO could be different. However, there are some basic cost-components such as capital costs, energy costs, and other operating and maintenance cost.

The total cost of ownership calculation method was defined in 1995 by Ellram [49], and it should be used as a purchasing tool helping us to understand the true costs of particular goods or services. Literature on total ownership costs of EVs is a relatively new and often, due to restricted statistics and information, limited in its scope. Some studies have relied on uncertain data and many assumptions, particularly in the case of BEVs [50].

The costs assumptions used in literature are very different. For example, length of ownership has very broad range in literature, e.g., 3 years [45], 5 years [51], 6 years [50], 15 to 20 years [43]. Also, assumptions regarding annual kilometers driven are very different, e.g., 15,000 km [45], 16,000 km [43]. The existing papers are mostly focusing on some specific country, car size, car type, etc. [45, 50].

The total costs related to the ownership of cars could be divided in fix and variable costs. The fix cost (capital cost) are easier to be evaluated than variable costs (operating costs) [52]. Total capital costs are dependent on initial expenditure to purchase the vehicle (vehicle purchase price) and possible resale value.

The vehicle purchase price is well known for all types of vehicles. Nevertheless, it is important to recognize that in the case of BEVs these costs are largely determined by battery costs. As an example, Figure 12 shows structure of the purchase price of midsize BEVs. Battery costs, which are very dependent on battery size, are largest contributor to the total car costs. For the most of BEVs share of battery costs in the total cost of car is between 23% and 58% [16]. To reduce high capital costs of EVs many governments are providing subsidies, and/or registration-tax reductions or exemptions. However, these measures are different from country to country and changeable over time [53–55].

The possible resale value of EVs is dependent from many parameters, such as total number of vehicle kilometers (vkm) driven, service history, general state, etc., and is quite uncertain especially in the case of BEVs and FCVs. In some studies, this value has been considered in the calculation of the TCO (e.g. [50]), and in some is assumed just one user over the whole lifetime of the car (e.g., [16]).

To estimate total operating costs of the car ownership is more difficult. These costs are sensitive on many features such as energy intensity of the car, driving behavior, holding period of the car, cost of electricity/fuels, taxes, maintenance and repair costs, parking costs, insurance, etc. Operating costs are quite different from country to country mostly due to different energy prices and policies applied.

Although assumptions made in literature are different as well as a level of details considered, most of studies are showing that EVs have disadvantage of being more expensive than conventional vehicles in spite of lower service and maintenance costs, better fuel economy and lower taxes.

In the following, we present our own approach to a comparative economic assessment of BEVs and FCVs in comparison to conventional ICE vehicles. A total cost of ownership approach is applied, (see, e.g., [16, 57]), considering capital costs, fuel costs and operating and maintenance (O&M) costs as major categories. This analysis takes into account the major costs related to car ownership. The capital costs (fix costs) encompass the acquisition costs of a car, including registration tax and value-added tax (VAT). The running costs include payments for fuel or electricity as well as excise taxes and (VAT).

$$C_{TS} = IC \cdot \alpha + EC \cdot EI \cdot vkm + C_{OM} \quad \left[Eur\ car^{-1}\ year^{-1}\right] \qquad (1)$$

where C_{TS} is total transport service cost per car and year; IC is total capital costs in EUR per car; α is a capital recovery factor; EC is energy costs in EUR per kWh, EI is energy intensity of

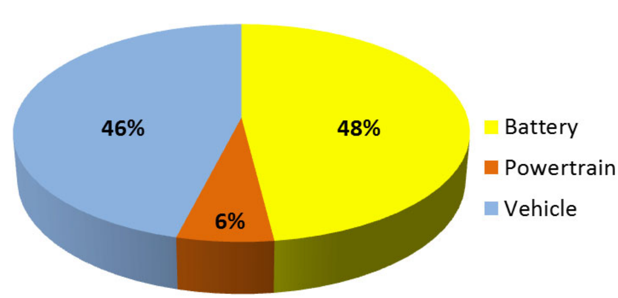

Fig. 12 Midsize EVs price structure, US 2016 [56].

the car in kWh per km, vkm is the number of specific kilometers driven per car and year, C_{OM} is the operating and maintenance costs per car and year.

To compare costs of BEVs and FCVs with conventional cars the costs per km driven (C_{km}) are calculated as:

$$C_{km} = \frac{IC \cdot \alpha}{vkm} + EP \cdot EI + \frac{C_{OM}}{vkm} \quad [Eur\ km^{-1}] \tag{2}$$

To show sensitivity of the total transport costs for BEVs and FCVs in comparison to gasoline cars, three different cases, a pessimistic, an average and an optimistic case, are calculated, see Figure 13. The pessimistic case has the highest total costs and it is associated with low number of specific vehicle kilometer driven (9,000 km), short depreciation time of 3 years and high interest rate (10%). An energy price and other operating and maintenance cost are assumed 20% higher than in the average case.

The average case applies for average assumptions as 12,000 km driven per year, an average depreciation time of 7 years, an interest rate of 5%. Energy prices and other operating and maintenance cost represent the average of EU-15 countries.

In the optimistic case, 16,000 km driven are assumed, as well as an average depreciation time of 12 years, an interest rate of 3%, and energy prices and operating and maintenance costs 20% lower than the current average.

The major finding from this comparison is that the capital costs are clearly the dominating cost category regardless, which interest rates, number of km driven and depreciation time are chosen. Capital costs represent between 60% and 90% of the total costs in all cases investigated. In the following, we describe the cost prediction analysis in detail.

In the future, based on technological learning it can be expected that the high capital costs of BEVs and FCVs will become cheaper and more competitive with conventional cars.

Technological learning can be illustrated by so-called experience or learning curves, see [16, 58]:

$$IC_t(x) = a \cdot x_t^{-b} \quad [Eur\ per\ car] \tag{3}$$

where IC is investment costs, a is the investment cost of the first unit, b is learning index, and x is the cumulative capacity (production) up to the year t.

In our model, we split up specific investment costs $IC_t(x)$ into a part that reflects the costs of conventional mature technology components $IC_{Con\_t}(x)$ and a part for the new technology components $IC_{New\_t}(x)$:

$$IC_t(x) = IC_{Con\_t}(x) + IC_{New\_t}(x) \tag{4}$$

For conventional mature technology components, no more learning is expected. For new technology components, Eq. (3) is applied.

In this paper, the assumptions regarding the future technological learning is based on an ambitious scenario for the diffusion of EVs worldwide [36]. Corresponding developments of the investment cost of the considered powertrains from 2015 to 2050 are summarized in Figure 14. The most remarkable cost decreases could be expected for BEVs and FCVs.

Moreover, due to further research and development energy intensity of all cars could be reduced. Figure 15 shows actual figures of the energy intensity of passenger cars (final energy consumption) and assumptions for development up to 2050 for the average car size of 80 kW. It can be seen, that in spite of expected decreases in the energy intensity of all vehicles analyzed, the large difference between the three car types will remain by 2050.

Based on the technological learning and further improvements in energy efficiency of cars, total transport costs of BEVs and FCVs in comparison to gasoline cars are calculated up to year 2050, see Figure 16. For all three types of car, a pessimistic, an average and an optimistic case is analyzed. The assumptions for these three cases are the same as in Figure 13. In the future, by 2050, significant cost reductions can be expected for the BEVs and FCVs in all cases analyzed.

Few major observations can be derived from Figure 16: (i) the TCO are very similar for all types of car in the corresponding specific category; (ii) capital costs are still dominating, although their percentage in the total costs is slightly lower than in 2016; and (iii)

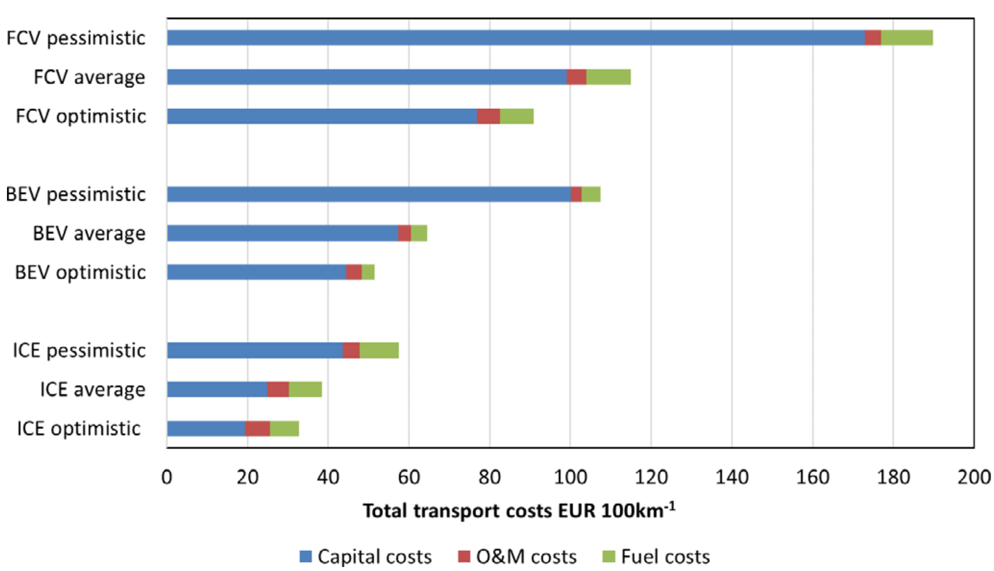

Fig. 13 Total transport costs in different cases analyzed, year 2016 (car power: 80 kW).

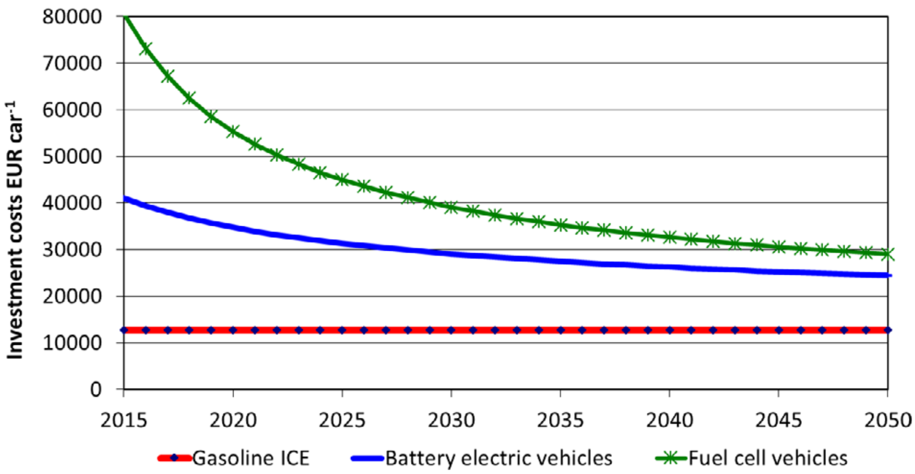

Fig. 14 Developments of the investment costs of the vehicles investigated due to technological learning up to 2050 (for average car size of 80 kW) [16, 34].

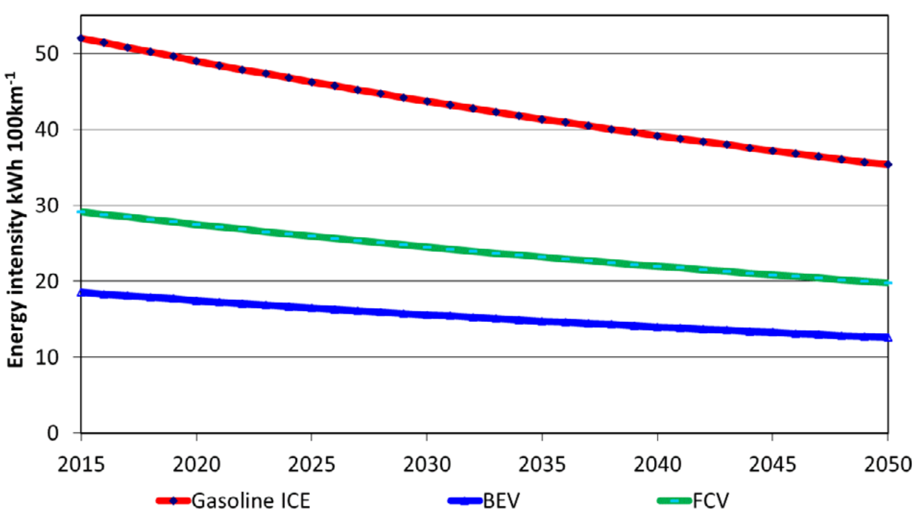

Fig. 15 Developments of the energy intensity of passenger cars up to 2050 (average car size of 80 kW) [16, 59–64].

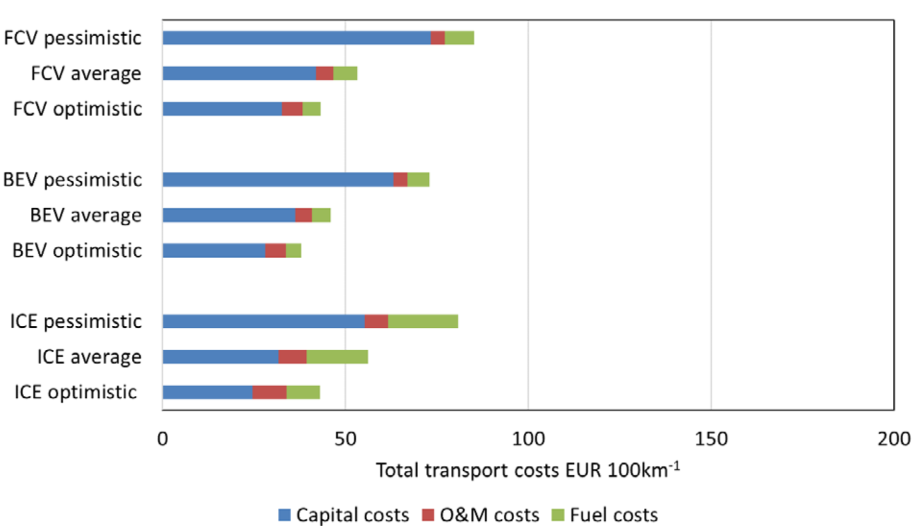

Fig. 16 Total transport costs in different cases analyzed, year 2050 (car power: 80 kW).

there are still remarkable differences depending on the chosen parameters for optimistic, average and pessimistic scenarios.

6 Environmental Aspects

Since the transport sector is one of the largest emitters of emissions, there is a huge need to facilitate more sustainability development of this sector. Electric vehicles offer a number of important environmental benefits, especial in polluted urban areas [65]. They have been recognized as an environmentally friendly technology, and their use is supported by different monetary- and non-monetary measures in many countries. The final goal of all these measures is to reduce energy use in the transport sector, especially use of fossil fuels, as well as the corresponding emissions.

However, to compare emissions of conventional cars with those of electric vehicles, it is important to analyze the whole energy supply chain including tank-to-wheel (TTW) emissions, which arise from a fuel use in the car, and well-to-tank (WTT) emissions, which are caused during production and supply of energy (fossil fuel, electricity or hydrogen), see Figure 17. Energy efficiency is one of the parameter which has impact on the total emissions. Although efficiency of different types of vehicles varies significantly, BEVs and FCVs have much higher efficiency than conventional ICE vehicles. The efficiency of ICE vehicles is about 20%, and of FCVs and BEVs is about 50% and 70%, respectively [1, 66]. In addition, the energy mix used for electricity generation and hydrogen production has significant impact on WTT, and finally also on total WTW emissions. However, as discussed above the energy mix used for electricity generation is very different from country to country, as well as environmental benefits of the EVs use.

Moreover, for a sound assessment of total emissions (CO_{2total}), also emis-

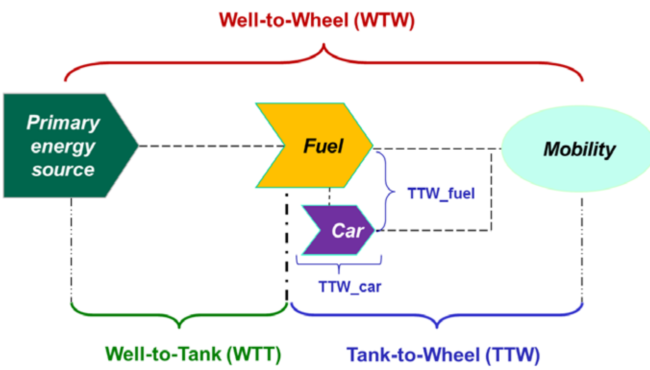

Fig. 17 Method of emission assessment.

sions caused during the car production and scrappage should be considered, see [67].

$$CO_{2_{total}} = CO_{2_{WTT_{fuel\_net}}} + CO_{2_{TTW\_fuel}} + CO_{2_{TTW\_car}} \quad [gCO_2\ km^{-1}] \tag{5}$$

where $CO_{2_{WTT_{fuel\_net}}}$ are emissions caused during production and supply of fuel/energy, $CO_{2_{TTW\_fuel}}$ are emissions arise from the fuel combustion in the car, and $CO_{2_{TTW\_car}}$ are emissions caused during the car production and scrappage.

The WTT emissions are strongly dependent on carbon content of the primary energy source, the energy production process and corresponding efficiency of the process used:

$$CO_{2_{WTT}} = \sum_{i=1}^{n} CO_{2_{PES}} \cdot \frac{S_{PES\_i}}{\eta_i} \quad [gCO_2\ kWh^{-1}] \tag{6}$$

where i is type of primary energy source, $CO_{2_{PES}}$ is carbon intensity of primary energy sources; S_{PES_i} is share of different primary energy sources in the fuel/electricity mix.

As an example, the specific WTT CO_2 emissions for different types of primary energy sources used for electricity generation are depicted in Figure 18, depending on the efficiency of the power plant. Using an average efficiency of 39% for coal power plants in the EU-15 884 g CO_2 per kWh are emitted. In the case of natural gas, this figure is 421 g CO_2 per kWh, assuming an average efficiency of 47% for natural gas plants. For electricity generation from RES a mix of one third of wind, hydropower and PV is assumed.

Figure 19 depicts WTW emissions of BEVs (excl. LCA emissions of the car) depending on the share of RES in the electricity mix compared to conventional ICE vehicles (for more details on data see [67]). According to this figure the use of 100% electricity from coal leads to higher CO_2 emissions than with conventional fossil fuel powered cars. Using 100% natural gas for electricity generation leads to savings of about 40% compared to gasoline ICE vehicles. The amount of CO_2 savings with BEVs is increasing with the increasing share of RES in electricity mix. For example in Figure 19 the point X refers to 50% RES and 50% coal in the electricity mix and ΔCO_{2X} is the corresponding emission saving due to BEV. This figure clearly depicts that the larger the share of RES is, the higher CO_2 savings are.

The emissions related to the car production and scrappage $(CO_{2_{TTW\_car}})$ are calculated as:

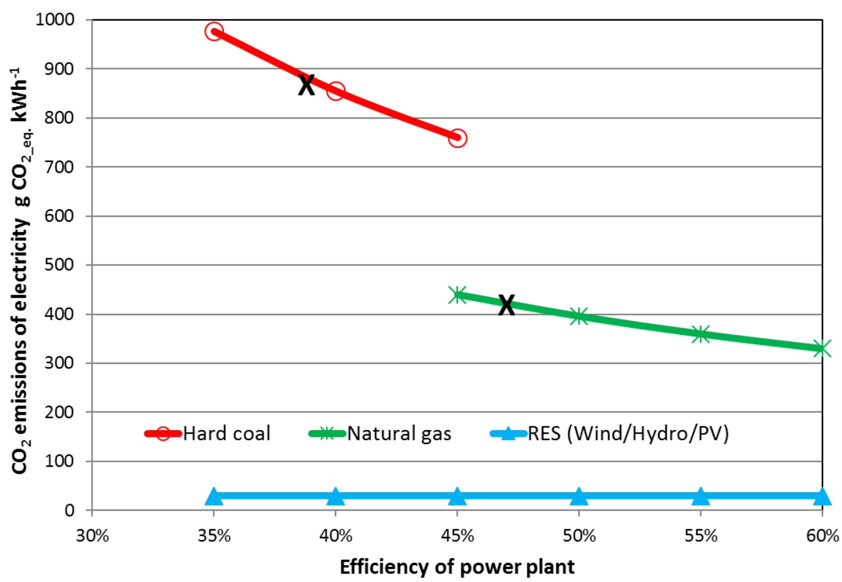

Fig. 18 CO_2 emissions of electricity generation depending on the efficiency of power plants (based on [67]).

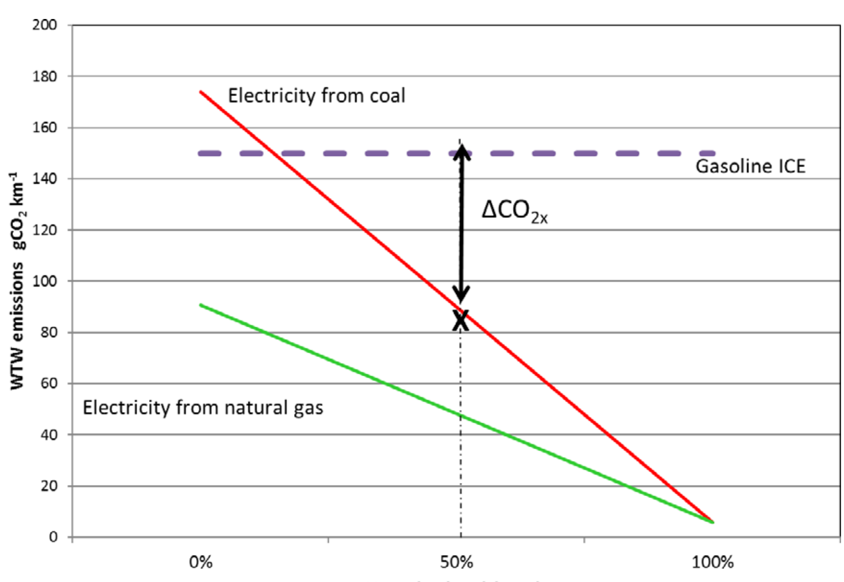

Fig. 19 WTW emissions (excl. LCA emissions of the car) depending on the share of RES in the mix of electricity generation (based on [67]).

$$CO_{2_{TTW\_car}} = \frac{CO_{2\,Car\,i}}{LT_i \cdot vkm_i} \quad [gCO_2\ km^{-1}] \qquad (7)$$

where CO_{2car} are total embedded emissions of the car, LT is lifetime of car, vkm is the number of specific km driven per car and year, i is a type of car.

In this paper we have calculated total CO_2 emissions of BEVs and FCVs for three different cases: optimistic, average, and pessimistic case, see Figure 20. Conventional gasoline ICE vehicles is taken here as the reference. For BEVs in the optimistic case only a mix of RES is used for electricity generation, in the average case natural gas, and in the pessimistic case coal. For FCVs in the optimistic case only a mix of RES is used for hydrogen production, in the average case natural gas from the EU, and in the pessimistic case natural gas from Russia. As seen from Figure 20 only in the optimistic cases, in which electricity and hydrogen are produced from RES, BEVs and FCVs show very significant advantage compared to the gasoline vehicle.

In addition to the fuel mix, the number of specific km driven has a significant impact on the specific CO_2 emissions per km driven. In Figure 21 the sensitivity of km driven per year on CO_2 emissions per km for vehicles analyzed is depicted. It can be seen that due to the impact of embedded emission of the cars, total CO_2 emission per km are decreasing with the increasing number of km driven, especially in the case of BEVs. The impact of km driven is significant, but still lower than the impact of the primary energy mix used.

In the future, further improvements in energy efficiency and car's production process can be expected, as well as increasing use of RES in the electricity generation and hydrogen production. Scenarios for the future CO_2-emissions in 2050 are depicted in Figure 22 for three different cases defined above (the same conditions as for 2016). Due to expected improvements, emissions of all cars in all cases should be lower that today. It is obvious that lowest emissions are in the optimistic case with electricity and hydrogen produced from RES. While in all cases FCVs show a better performance than the gasoline car, in the pessimistic case BEVs have still slightly higher emissions in comparison to conventional cars. The embedded emissions of the cars have considerable impact on the total emissions in every case, even for the conventional cars.

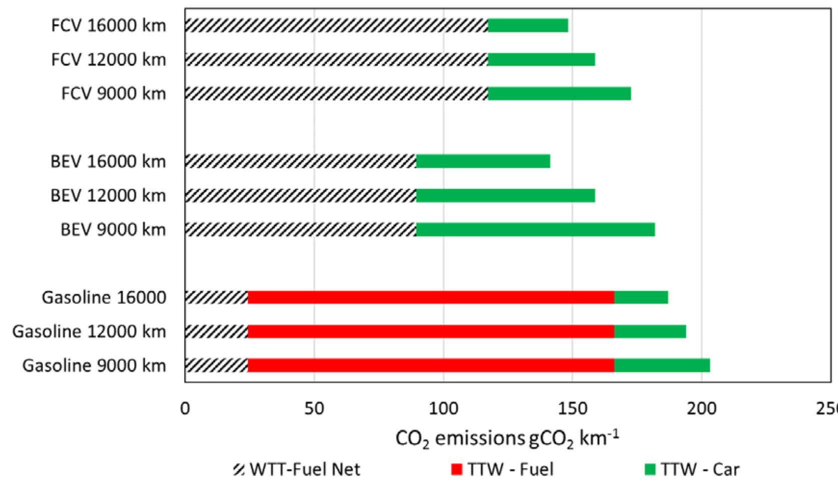

Fig. 21 Total CO_2 emissions per km driven for different numbers of vehicles km driven for different types of passenger cars in 2016.

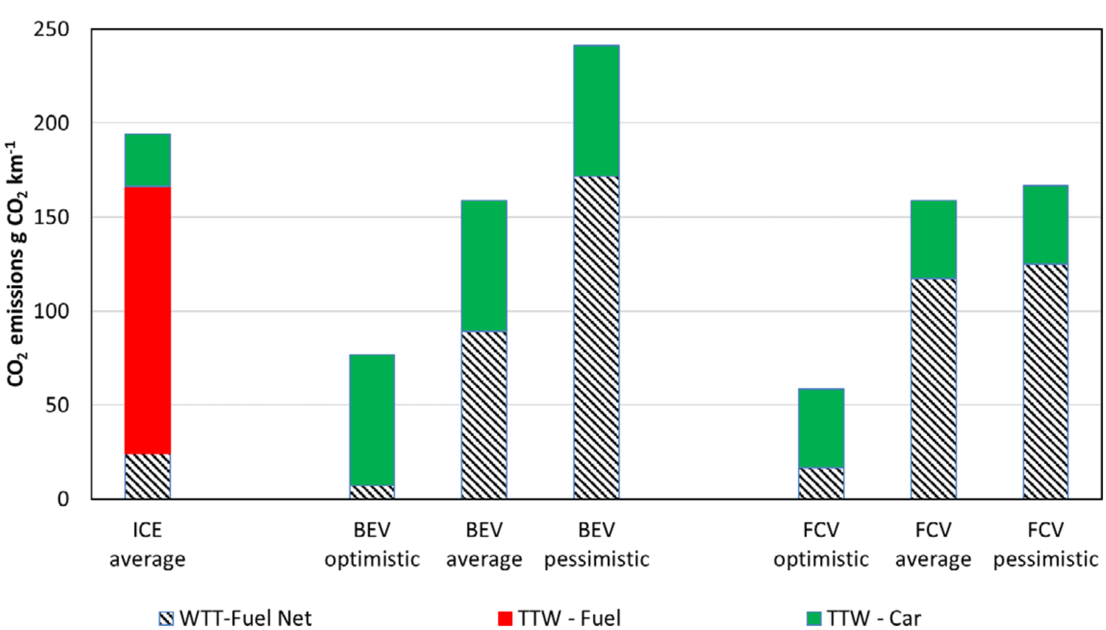

Fig. 20 CO_2 Emissions of different types of passenger cars for optimistic, average and pessimistic assumptions in 2016.

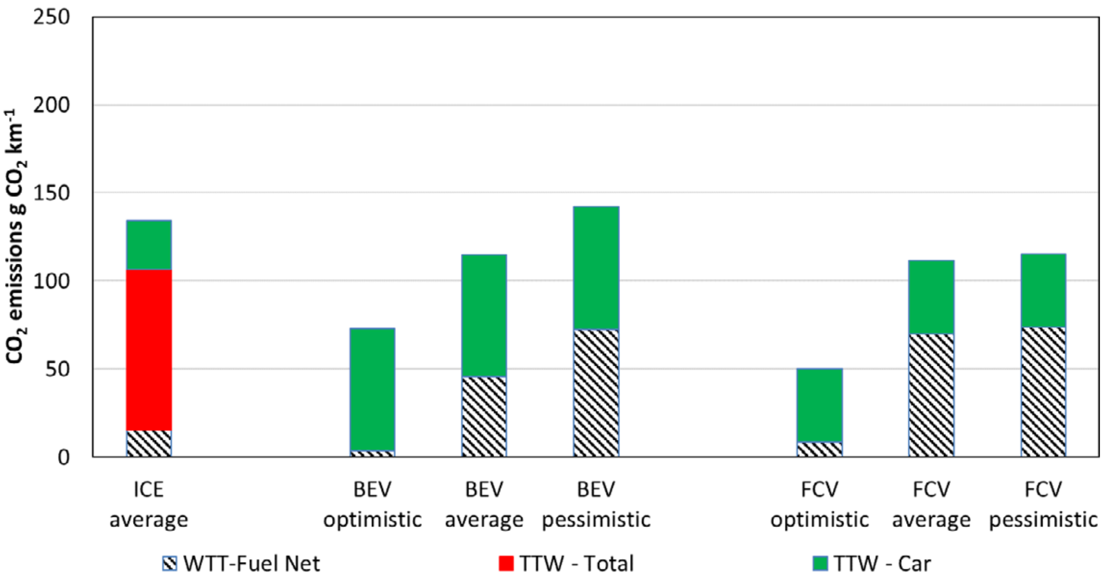

Fig. 22 CO_2 Emissions of different types of passenger cars for optimistic, average and pessimistic assumptions in 2050.

7 Conclusions

Due to the pressing environmental problems, the interest in EVs has increased significantly over the last decade. Although, different types of EVs are available on the market, the largest contribution to the reduction of environmental problems could be provided by zero-emission vehicles, such as BEVs and FCVs. Each of these vehicles has several advantages and disadvantages:

(i) Currently, FVCs have significantly higher capital costs than BEVs but they also have the potential for considerable cost reduction in the future;

(ii) FCVs, compared to BEVs, already have driving ranges comparable to conventional cars. In addition, they have significantly shorter refueling times, approx. 3 min;

(iii) The lifetime of FCVs is comparable to conventional cars. In the case of BEVs, battery lifetime is very sensitive to climate conditions, overcharging, charging/discharging rates;

(iv) Both, FVCs and BEVs, have significantly lower total WTW emissions compared to conventional cars when using hydrogen, respectively electricity produced from RES.

The major problem of BEVs and FCVs today is the high purchase price of the car in comparison to that of conventional ICE vehicles. However, through further research work and the improvement of battery and fuel cell performances, as well as technological learning, the competitiveness of these cars will be higher in the future. This analysis has shown that:

(i) The major uncertainty regarding the future prospects of BEVs and FCVs is how fast technological learning will take place, especially with respect to batteries and fuel cells.

(ii) In addition, supporting policies can make EVs more competitive on the market. Besides directly-provided monetary measures (e.g., subsidies, tax exemptions and reductions), and non-monetary measures (e.g., the permission for EVs to enter zero-emission zones or use bus lanes), also access restrictions for ICE vehicles and bans on diesel cars, make EVs more attractive.

(iii) Moreover, it is important to stress that the full environmental benefit of BEVs and FCVs is related to the mix of the primary energy sources used for electricity generation and hydrogen production. The increasing use of RES in electricity generation, one of the priorities of the European energy policy, will make EVs more environmentally friendly.

(iv) Since total emissions are also dependent on the embedded emissions of cars, the lifetime of cars and their usage per year have a significant impact on the total emissions per km driven.

(v) BEVs used just for short trips in the city could have similar total emissions and higher costs in comparison to conventional cars. At this relatively early stage of the EVs use, it is recommended to support their use in different kinds of fleets (e.g., smaller delivery cars, taxis or car-sharing), which have high travel activity and operate in smaller areas (cities) so that charging infrastructure can be provided more easily.

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