On the prospects of increasing energy efficiency in car transport by promoting electric and hydrogen vehicles

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Keywords

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Abstract

Transport is still the end use sector with highest increasing emissions and lowest energy efficiency. Alternative powertrains like electric motors and fuel cells based on electricity and hydrogen are considered as important means to cope with environmental problems in transport.

The core objective of this paper is to investigate the market prospects increasing energy efficiency in car transport by promoting battery electric, hybrid and fuel cell vehicles from a technical energetic and an economic point-of-view in a dynamic framework in an optimistic scenario up to 2050 in comparison to conventional passenger cars.

Our method of approach is based on life-cycle-analyses, dynamic economic assessments (incl. technological learning) and price as well as policy scenarios e.g. for taxes.

The most important results are: (i) The by far most energy efficient solutions are battery electric vehicles (BEV) and fuel cell vehicles (FCV) yet only if the electricity is generated from renewable energy sources (RES) as wind, hydro or PV are used; (ii) energy losses in the Well-to-Wheel chain for providing the energy service mobility will be reduced due to technological progress by 30 % to 50 % up to 2050 with respect to all technologies; (iii) Despite the efficiency gap to conventional cars will become smaller because higher technical improvement potentials for especially hybrid electric vehicles (HEV) exist, also in the long run BEV and FCV will remain the most efficient options; (iv) the major uncertainty regarding BEV and FCV is how fast cost reduction due to Technological Learning will take place especially for batteries and fuel cells; (v) Hybrid electric vehicles are currently the most efficient and most effective fossil fuels-based vehicles; Yet they are not considered as Zero-emission cars proper for driving in cities; (vi) Finally, CO_2 costs (e.g. taxation) will play a crucial role for the final future fuel mix. E.g. Oslo in Norway is a city with one of the highest penetrations of BEVs in the world. One major reason is that – among other incentives – the driving costs of conventional cars are very high compared to rather cheap electricity costs for BEV drivers.

This leads to the final conclusion that the most efficient types of vehicles will in future only play a significant role if the proper mix of CO_2-taxes, intensified R&D, and corresponding riding down the Learning Curve (e.g. batteries for EVs and fuel cells) as well as non-monetary incentives is implemented timely.

Introduction

Alternative powertrains like battery electric vehicles (BEV), hybrid electric vehicles (HEV) and hydrogen-based fuel cell vehicles (FCV) are considered as environmentally benign alternatives to fossil fuel based conventional passenger cars. However, the high costs are still barriers for a broad market breakthrough of these vehicles.

The core objective of this paper is to investigate the future market prospects of alternative powertrains like BEV, HEV and FCV in a dynamic framework till 2050 in comparison to conventional passenger cars for average conditions of EU-15 countries. In particular we focus on an optimistic scenario based on most favourable conditions for alternative technologies. With respect to EVs in this paper we do not specifically

focus on mixed categories as range extended EV and plug-in hybrids (PHEV). Depending on the mix between electricity and gasoline (or diesel) as fuels used they are placed somewhere between BEV and HEV. This work builds on [1], [2] and [3]. In Ajanovic [3] a comprehensive analysis of all types of EVs is provided. The major conclusion is that most important for a successful future dissemination of EVs are that the source for electricity generation are renewables and that significant Learning with respect to the battery is achieved.

Other important papers of relevance are [4], [10] and [14]. One of the first comparative analysis of battery electric, hydrogen fuel cell and hybrid vehicles and their role in a future sustainable road transport system has been conducted by Offer et al [10]. They conclude that the best path for future development of EVs is the FCV. Van Vliet et al [14] conducted a techno-economic comparison of series hybrid, plug-in hybrid, fuel cell and regular cars. They examine the competitiveness of series hybrid compared to fuel cell, parallel hybrid, and regular cars. Their major finding is that the fuel cell car remains uncompetitive even if production costs of fuel cells come down by 90 %. Plug-in hybrid cars are competitive when driving large distances on electricity, and/or if cost of batteries come down substantially.

Special attention is put on the issue of specific km driven per car per year as a major parameter for economic assessment, see in Annex tables for details.

For electricity and hydrogen (H2) we also consider different fuel mixes from fossil versus renewable energy sources (RES). This is relevant to identify the environmental performance which is further on translated into corresponding costs of CO_2 of fuels by introducing a CO_2 tax. Hence, in the economic analysis we also consider the potential effects of CO_2 taxes.

With respect to the time frame analysed the following remark is important: It is evident that up to 2050 fundamental changes in the structure of passenger transport may take place with severe impact on shares of different technologies, modal splits as well as organisation of living, labour and leisure time. However, these changes are not subject of this paper and do also not impact our results. The only dimension where we have to rely on an external scenario are learning rates for BEV and FCV used for the final economic analysis.

Method of Approach

The method of approach applied in this work is based on a scenario with favourable conditions for the development of the energy performance of conversion efficiencies in the whole energy service mobility providing chain. We conduct a dynamic technical and economic analysis and investigate when in future HEV, BEV and FCV could become – under most favourable conditions – economically competitive compared to conventional gasoline and diesel cars. In addition we analyze the performance of flex-fuel vehicles using bioethanol.

To evaluate the economics we compare the transport service costs per 100 km driven and the total costs per year. In this context different driving distances play a role. Our formal economic framework starts with calculating the total driving costs C_{drive} per year (All cost values in this paper refer to EUROs of 2010):

$$C_{drive} = IC\ \alpha + P_f FI\ skm + C_{O\&M} \quad [€/car/year] \qquad (1)$$

The costs per km driven C_{km} are calculated as:

$$C_{km} = \frac{IC \cdot \alpha}{skm} + P_f \cdot FI + \frac{C_{O\&M}}{skm} \quad [€/100\ km\ driven] \qquad (2)$$

where:

IC	investment costs [€/car]
α	capital recovery factor
skm	specific km driven per car per year [km/(car.yr)]
P_f	energy price incl. taxes [€/kWh]
$C_{O\&M}$	operating and maintenance costs
FI	energy consumption [kWh/100 km]

The fuel price depends on the cost of fuel C_f, and possible VAT, excise and CO_2 taxes:

$$P_f = C_f + \tau_{CO_2} + \tau_{VAT} + \tau_{exc} \qquad (3)$$

To capture the dynamic effects of changes in investment costs of powertrains over time we apply the approach of technological learning (TL). We use equ. (4) to express an experience curve by using an exponential regression depending on investment cost of new technology components ICNew_t(x), the learning index b and the investment cost of the first unit a, see e.g. [9]:

$$IC_{New\_t}(x) = a \cdot x_t^{-b} \quad [€/car] \qquad (4)$$

A note: These investment costs are related to the whole car.

Technical and Ecological Prospects

For the economic assessment the energetic conversion and the CO_2 emissions – on which the CO_2 tax is based – are the major technical impact parameters. In the following we compare the current state and show the possible developments the well-to-wheel (WTW) CO_2-equ balances and the fuel intensity in kWh/100 km driven up to 2050.

Figure 1 and Figure 2 compare the well-to-tank (WTT-), tank-to-wheel (TTW-) and WTW net CO_2 emissions of conventional and flex-fuel vehicles as well as BEV, HEV and FCV from various energy sources in 2012 and 2050 for the average of EU-countries. The difference in the options of BEV presented is the primary energy source of electricity. On the one hand, this source are renewables (in this case a mix of hydro and wind), on the other hand electricity is generated in coal-fired or naturals gas-fired power plants. This is of tremendous importance for the environmental assessment of BEV conducted in this paper. Similar is the difference between the presented FCV. A major perception of this figure is that despite BEV and FCV do not emit CO_2 in the TTW-phase they are environmentally unfavourable to conventional cars if the electricity used is generated in fossil power plants.

The historical figures and assumptions for the expected future developments of passenger cars' fuel intensities in the scenarios up to 2050 (for average car size of 80 kW) are described in Figure 3. Note, that the steepest decrease in fuel intensities took already place before 2011 as a first result of the European Commission to improve the efficiency of cars. For further details on life-cycle energy balances see [1].

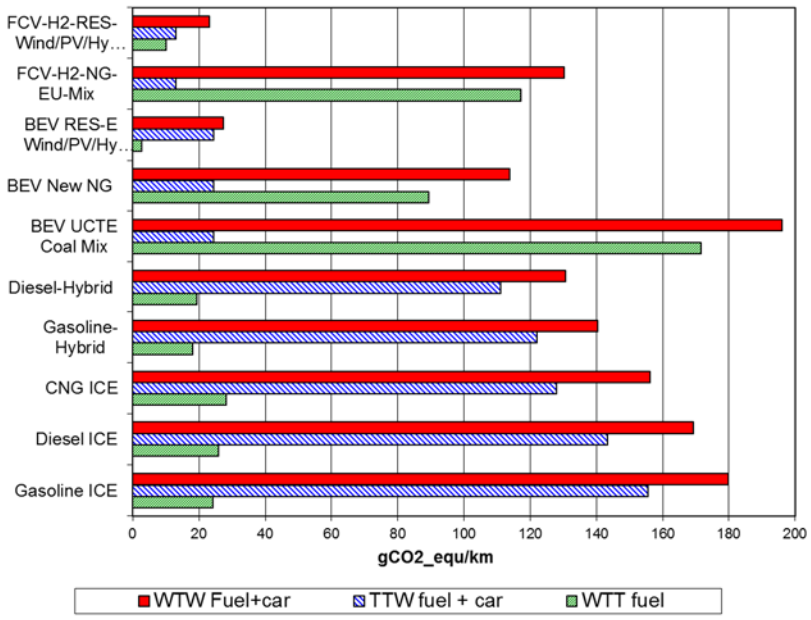

Figure 1. WTT-, TTW- and WTW net CO_2 emissions of various vehicles and energy sources in 2012 for the average of EU-15 countries (Car size: 80 kW, details see Table A-2). Abbreviations: NG – Natural gas, CNG – compressed natural gas, H2 – Hydrogen).

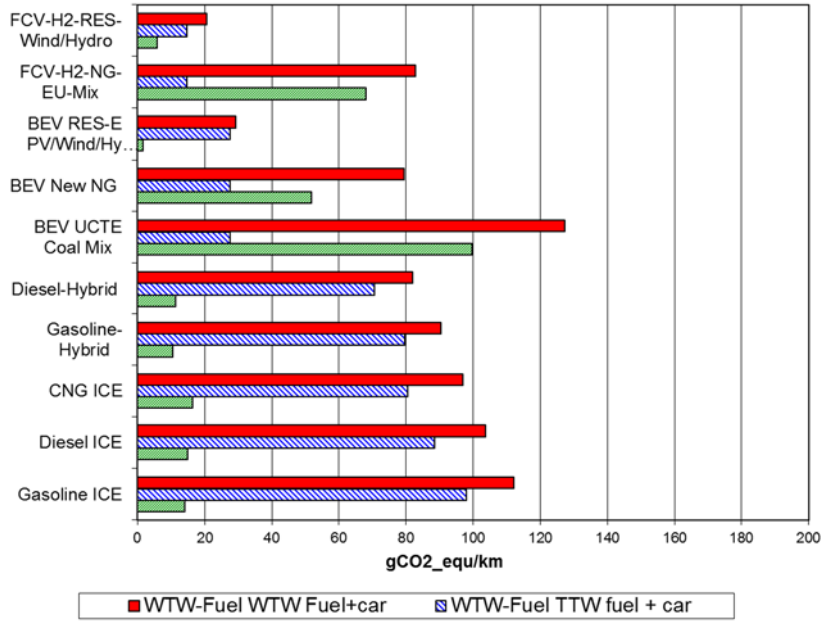

Figure 2. WTT-, TTW- and WTW net CO_2 emissions of various vehicles and energy sources in 2050 for the average of EU-15 countries (Car size: 80 kW, details see Table A-2).

Technological Learning

With respect to the future development of the investment costs of alternative powertrains it is expected that they will be reduced through technological learning. Technological learning (TL) is illustrated for many technologies by so-called experience or learning curves. In our model we split up specific investment costs $IC_t(x)$ into a part that reflect the costs of conventional mature technology components $IC_{Con\_t}(x)$ and a part for the new technology components $IC_{New\_t}(x)$.

$$IC_t(x) = IC_{Con\_t}(x) + IC_{New\_t}(x) \quad (5)$$

where:

$IC_{Con\_t}(x)$ specific investment cost of conventional mature technology components (€/kW)

x cumulative capacity up to year t (kW)

For $IC_{Con\_t}(x)$ no more learning is expected. For $IC_{New\_t}(x)$ we consider a national and an international learning effect:

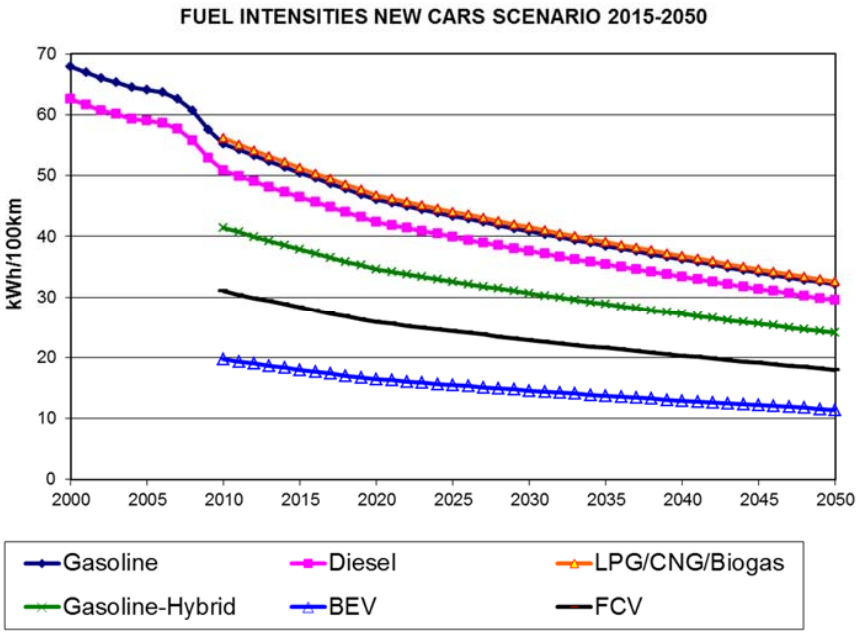

Figure 3. Historical developments of passenger cars' fuel intensities (final energy consumption) and assumptions for development up to 2050 (for average car size of 80 kW) (References: [3], [5], [6], [7], [8], [11]).

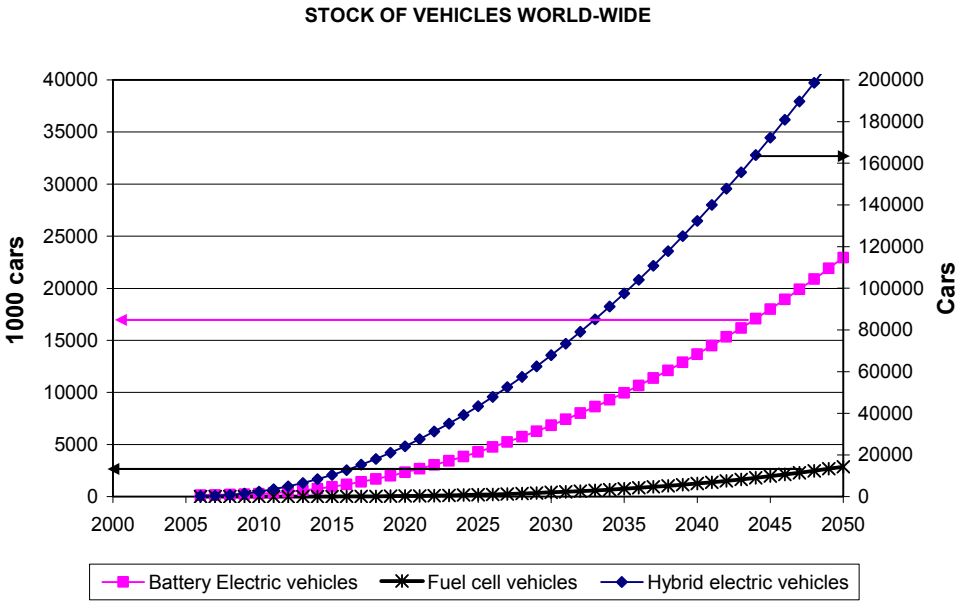

Figure 4. Over-all scenarios for world-wide wide market diffusion of HEV, BEV and FCV 2010–2050 (Source: [3], [6]) .

$$IC_{New\_t}(x) = IC_{New\_t}(x_{nat\_t}) + IC_{New\_t}(x_{int\_t}) \qquad (6)$$

where:

$IC_{New\_t}(x_{nat\_t})$ specific national part of $IC_{New\_t}(x)$ of new technology components (€/kW)

$IC_{New\_t}(x_{int\_t})$ specific international part of $IC_{New}\_t(x)$ of new technology components (€/kW)

For both components of IC_{New_t} (x) we use (4) to express an experience curve.

The assumptions for analyzing the possibilities of TL in future in this paper based on an ambitious scenario for the development in world-wide market diffusion of the analyzed car types as depicted in Figure 4. Note that also the source for these assumptions IEA (2011) considers this scenario as an optimistic one. In this study the decision for market diffusion is based on several expected effects as cost reduction, procurement and higher registration taxes for conventional cars.

Based on TL all of these cars should have already become cheaper over the past decades. However, aside from increases in average power of these cars – which is not the focus of this paper – improvements in the service quality e.g. the electronics – of the car have taken place and these have virtually eaten up the largest part of the cost savings which have incurred for the "naked" car due to learning. The values considered refer to an average 80 kW car.

Figure 5 summarizes the investment cost developments of the considered powertrains from 2012 to 2050. Of course, the most remarkable cost decreases are expected for BEV and FCV.

Economic Assessment

For the economic analyses we consider investment costs, operating and maintenance costs, fuel costs and the relevance of CO_2 taxes in the cost structure. Moreover, we use different skm/year for different car categories, see Tables A-1 and A-2 in the Annex. Our analysis starts with the fuel costs. Figure 6 compares the scenarios for the development of the fuel costs (incl. taxes) of the service mobility per 100 km driven from 2010 to 2050.

In our optimistic scenario CO_2 taxes replace excise taxes in 2016 and increase up to 2050 by 1.5 cent/kg CO_2 and year. In

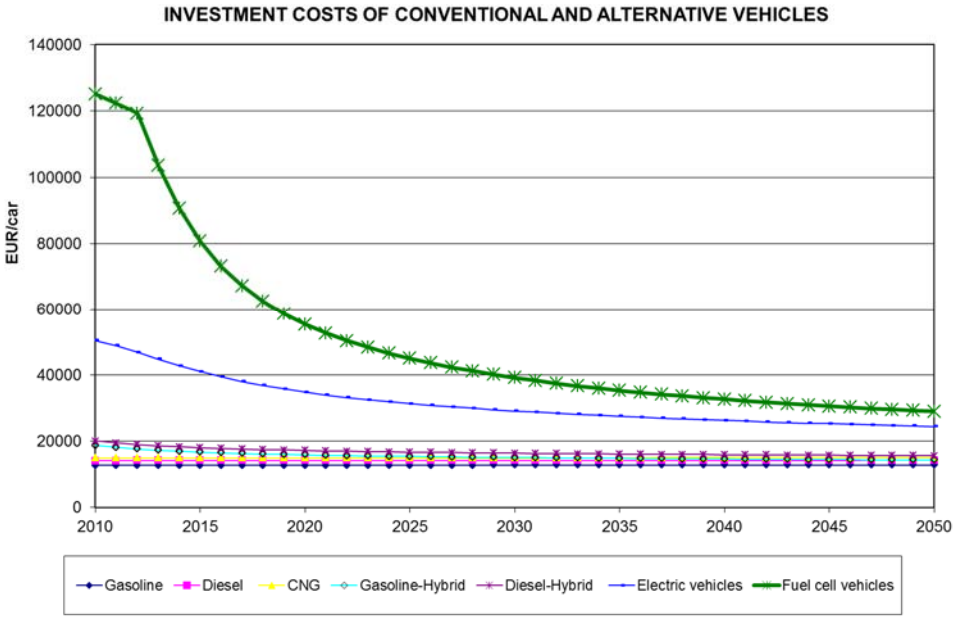

Figure 5. Development of investment costs of the considered powertrains over time considering Technological Learning and service increases 2012–2050.

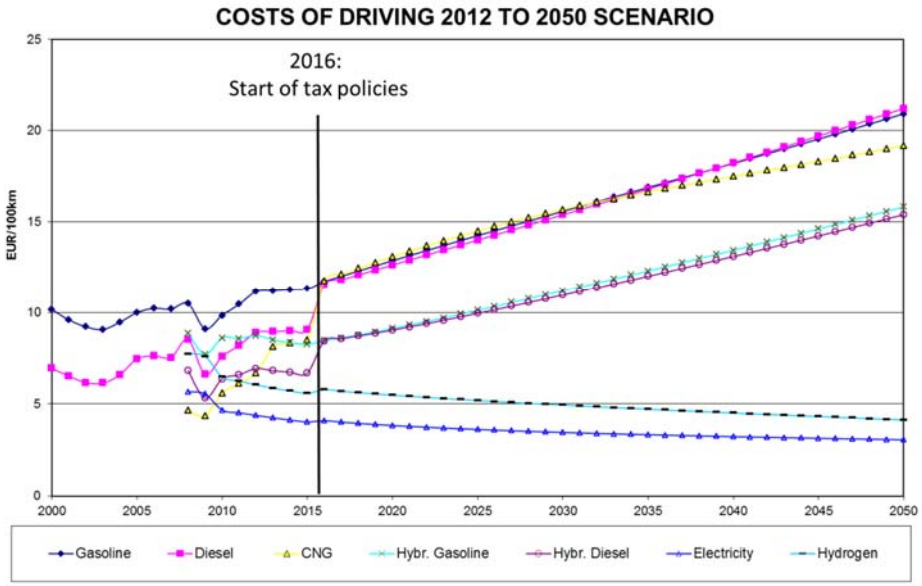

Figure 6. Scenario of fuel costs incl. taxes per 100 km from 2012–2050 (in Euros of 2010).

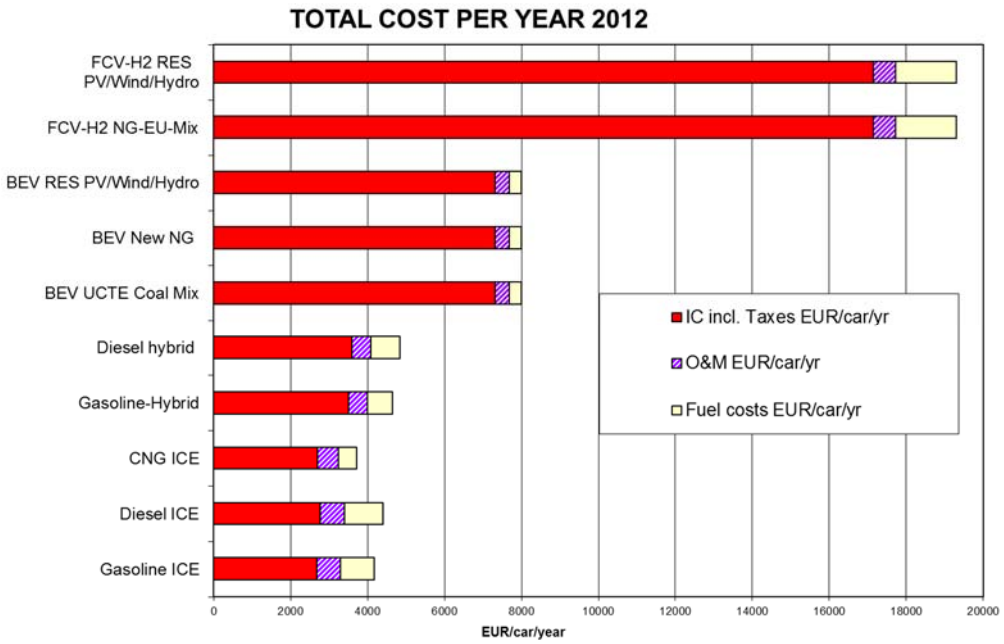

Figure 7. Total costs of driving passenger cars per per year in 2012 (average car capacity: 80 kW, different driving ranges based on historical experience, for details see Table A-1).

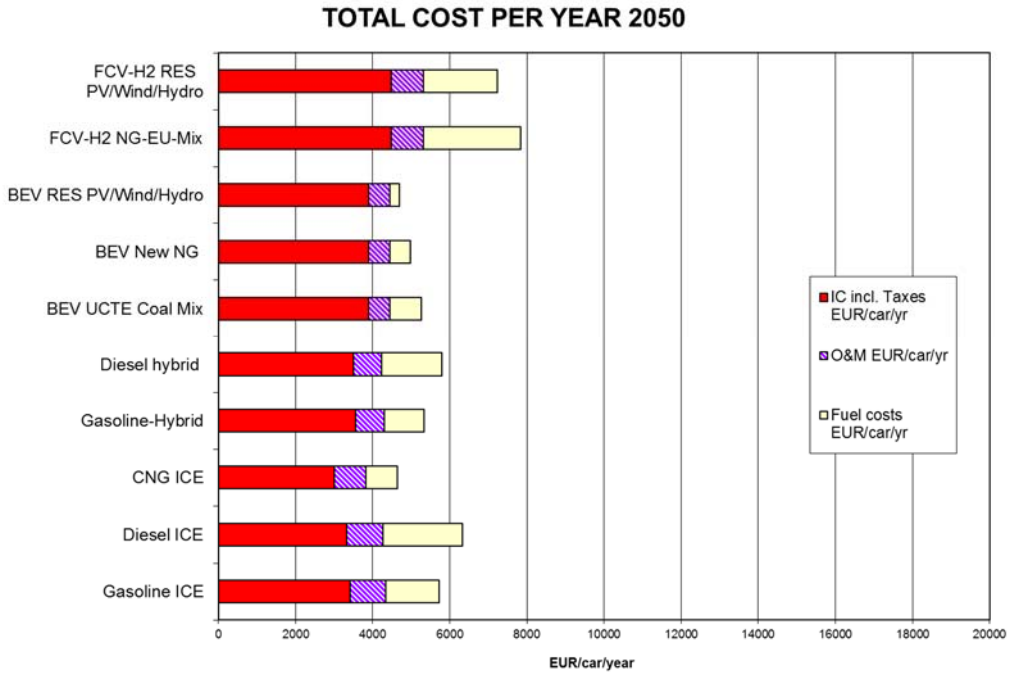

Figure 8. Total costs of driving passenger cars per per year in 2050 (average car capacity: 80 kW, different driving ranges based on historical experience, for details see Table A-2).

addition the costs of Petrol, diesel and CNG increase by 3 % per year. The resulting results in 2050 (in prices of 2010) are documented in Table A-2. The Fuel costs for driving remain cheapest for electricity but costs of hydrogen cars come closer and are remarkably cheaper than fossil fuels and biofuels. Due to the introduced CO_2 taxes price increases are highest for the fossil fuel driven vehicles.

Figures 7 and 8 describe the cost structure of total costs of driving for different types of cars in 2012 and in 2050. Note, that the costs of diesel are higher than petrol because of more km driven per year and because of higher investment costs of diesel cars, see also the tables in the Annex. We can see that the advantages of alternative powertrains regarding lower fuel costs are more than compensated by higher capital costs in 2012, see

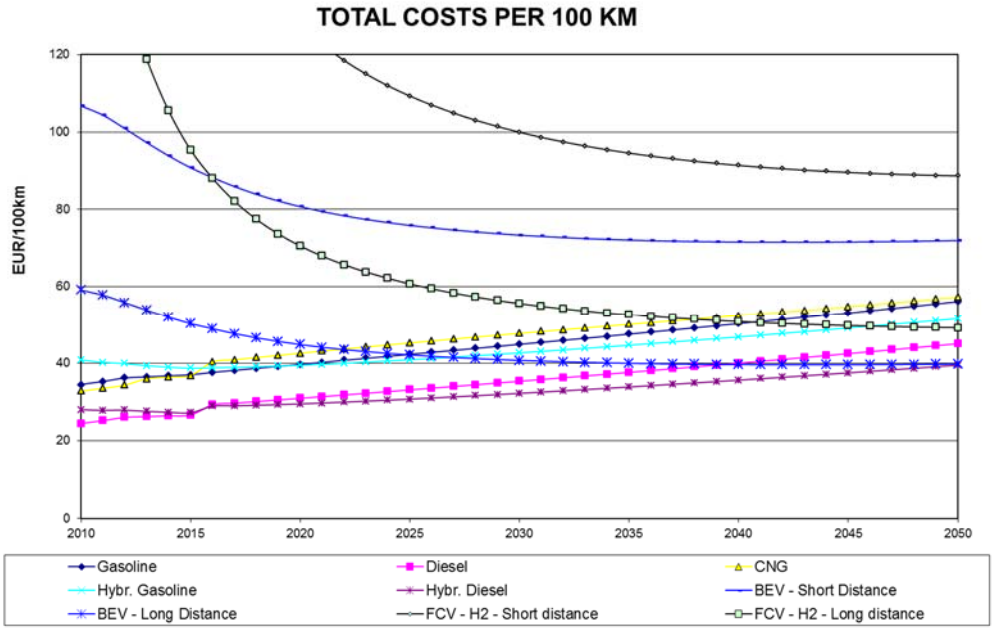

Figure 9. Development of the total costs of mobility (incl. capital, ownership and fuel costs) per 100 km driven of different types of passenger cars in 2010–2050 (for details see Table A-1 and Table A-2, long distance: 15,000 km/yr, short distance 8,000 km/yr).

Figure 7. For specific details regarding underlying assumptions for these calculations e.g. maintenance costs, depreciation time of vehicle, annual km driven, see Table A-1 and Table A-2.

The specific capital costs are the component of the driving costs with the highest magnitude for all investigated alternative powertrains (and conventional cars as well). With respect to HEV, BEV and FCV of course also the actual costs for batteries as well as for fuel cells are taken into account. However, these costs can be reduced until 2020 based on technical improvement potentials, Figure 7. By 2050 costs of most cars will even out, see Figure 8. Yet, diesel cars still remain cheapest, mainly because of more km are driven in these cars and capital costs are distributed to larger distances.

The development of the total costs of service mobility per 100 km driven of different types of passenger cars from 2010 to 2050 is compared in Figure 9. We can see that total costs for conventional cars increase slightly – mainly because of the CO_2 taxes introduced and increases in fuel costs – while driving costs of BEV and FCV decrease remarkably. This happens mainly due to TL that reduces the costs of batteries and fuel cells.

A paradox aspect that can be seen from Figure 9 is that economics of alternative powertrains increases with number of km driven per car and year. This implies that on the one hand it is more favourable to substitute diesel cars by EV and on the other hand it emphasizes the problem of range of battery.

Conclusions

The following conclusions are all based on the results of an optimistic scenario. No range is presented in this paper but it is obvious that all developments would be less favourable having e.g. lower fossil fuel prices and lower learning rates.

The major conclusions of this analysis are: From a technical point-of-view BEV and FCV are currently clearly preferable to conventional cars regarding environmental performance as well as energetic conversion efficiency. Yet, this applies only if electricity respectively hydrogen used is produced from RES.

Regarding the economic competitiveness of alternative powertrains compared to conventional vehicles various scenarios are possible. In the most favourable case – long driving distances – BEV will become fully competitive in the market by about 2025. FCV will become competitive even later, by about 2040. Also in this case optimistic assumptions are used in favour of this technology. HEV are already today a feasible technical option which combines the advantages of both electric drives and ICE-vehicles at rather moderate additional costs. Finally, an important finding is that by 2050 the total overall driving costs of most analysed fuels and powertrains will almost even out.

The major uncertainty remaining regarding BEV and FCV is how fast technological learning will take place especially for the battery and the fuel cells.

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Annex

Table A-1. Data used for calculations for year 2012 (own analyses, based on [2], [3], [5], [7], [12]).

CAR TECHNOLOGY:	**CRF: 0.15**	**Depreciation time: 8 years , Interest rate: 5%**								
2012		Fuel Prices of 2012			Investment	Operation&	km driven	WTT_Fuel		Fuel
		incl. Tax	tax (Min: 20	excl. Tax	costs incl.taxes	maintenance	per	Fossil	Renewable	intensity
	UNIT	EUR/UNIT	EUR/UNIT	EUR/UNIT	EUR/car	EUR/car/yr	year	kWh/kWh	kWh/kWh	kWh/100km
Gasoline ICE	EUR/l Gaso	1.352	0.792	0.560	17335	624	10499	1.17	0.00	53.78
Diesel ICE	EUR/l Diese	1.181	0.531	0.650	17919	624	16663	1.19	0.00	50.77
CNG ICE	EUR/kg CN	1.000	0.250	0.750	17427	550	10483	1.25	0.00	56.12
Gasoline-Hybrid	EUR/l Gaso	1.352	0.792	0.560	22635	499	10499	1.17	0.00	40.34
Diesel-Hybrid	EUR/l Diese	1.181	0.531	0.650	23219	499	16663	1.19	0.00	38.08
BEV UCTE Coal Mix	EUR/kWh	0.201	0.041	0.160	47266	382	7904	3.00	0.00	19.70
BEV New NG	EUR/kWh	0.201	0.041	0.160	47266	382	7904	1.80	0.00	19.70
BEV RES-E Wind/PV/Hydro	EUR/kWh	0.201	0.041	0.160	47266	382	7904	0.02	1.04	19.70
FCV-H2-NG-EU-Mix	EUR/kg H2	11.543	1.673	9.870	110851	573	14821	1.50	0.00	31.00
FCV-H2-RES-Wind/PV/Hydro	EUR/kg H2	11.543	1.673	9.870	110851	573	14821	0.03	1.64	31.00

Table A-2. Data used for calculations for year 2050 (own analyses, based on [2], [3], [6], [12])

CAR TECHNOLOGY:	**CRF: 0.15**	**Depreciation time: 8 years , Interest rate: 5%**								
2050		Fuel Prices of 2050						WTT_Fuel		Fuel
		incl. Tax	tax (Min: 20	excl. Tax	IC incl. Taxes	O&M		Fossil	Renewable	intensity
	UNIT	EUR/UNIT	EUR/UNIT	EUR/UNIT	EUR/car	EUR/car/yr	km/year	kWh/kWh	kWh/kWh	kWh/100km
Gasoline ICE	EUR/l Gaso	4.775	2.498	2.277	21998	929	8253	1.17	0.00	31.22
Diesel ICE	EUR/l Diese	5.446	2.803	2.643	21490	929	13098	1.19	0.00	29.47
CNG ICE	EUR/kg CN	5.857	2.807	3.050	19375	819	8240	1.25	0.00	32.58
Gasoline-Hybrid	EUR/l Gaso	4.775	2.498	2.277	22963	743	8253	1.15	0.00	23.42
Diesel-Hybrid	EUR/l Diese	5.446	2.803	2.643	22563	743	13098	1.17	0.00	22.10
BEV UCTE Coal Mix	EUR/kWh	1.426	0.604	0.822	25137	557	6288	2.60	0.00	11.44
BEV New NG	EUR/kWh	0.883	0.324	0.559	25137	557	6288	1.40	0.00	11.44
BEV RES-E PV/Wind/Hydro	EUR/kWh	0.351	0.054	0.298	25137	557	6288	0.01	1.03	11.44
FCV-H2-NG-EU-Mix	EUR/kg H2	43.218	11.398	31.820	28968	836	11791	1.39	0.00	18.00
FCV-H2-RES-Wind/Hydro	EUR/kg H2	29.924	4.751	25.173	28968	836	11791	0.02	1.50	18.00