An economic, ecological and energetic assessment of battery electric, hybrid and fuel cell cars

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Abstract — **The core objective of this paper is to conduct an integrated assessment of battery electric (BEV), hybrid and fuel cell vehicles (FCV) from an ecological, energetic and economic point-of-view in a dynamic framework up to 2050 in comparison to conventional fossil fuel based cars. The major results and conclusions of this analysis are: From energetic as well as from ecological point-of-view BEV and FCV are currently clearly preferable to conventional cars. Yet, this applies only if the electricity respectively the hydrogen used in the cars is produced from renewable energy sources. With respect to the economic competitiveness of alternative powertrains compared to conventional vehicles in the most favorable case BEV will enter the market by about 2025. FCV will become competitive even later, by about 2040.**

Keywords- battery electric vehicles, fuel cell vehicles, ecological performance, economics, technological learning

I. 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 cars. However, the high costs are still barriers for a broad market breakthrough of these vehicles.

The core objective of this paper is to conduct an integrated assessment of BEV, HEV and FCV from an ecological, energetic and economic point-of-view in a dynamic framework up to 2050 in comparison to conventional internal combustion engine (ICE) vehicles based on fossil fuels for average conditions of EU-15 countries. This work builds on [1] and [2]. Special attention is put on the issue of kilometers driven per car and year since it has a significant impact on economic assessment.

We also consider different fuel mixes for electricity and hydrogen (H_2) from renewable versus fossil energy sources. 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.

The following remark is important with respect to the time frame analyzed: 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 organization of living, labor and leisure time. However, these changes are not subject of this paper and do also not impact our results. The only dimensions where we have to rely on an external scenario are learning rates for BEV and FCV used for the final economic analysis.

II. METHOD OF APPROACH

Our method of approach is based on a scenario with favorable conditions for the development of the energetic 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 favorable 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 100km driven. In this context different driving distances play a role. Our formal economic framework starts with calculating the total driving costs C_{Drive} per year:

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

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 year)]
P_f…….Fuel price including taxes [€/litre]
$C_{O\&M}$…Operating and maintenance costs
FI……..Fuel intensity [litre/100 km]

The fuel price depends on the cost of fuel C_f, Value add tax τ_{VAT}, excise tax τ_{exc} and possible CO_2 taxes τ_{CO2}:

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

To capture the dynamic effects of changes in investment costs of powertrains over time we apply the approach of technological learning (TL). We use eq. (4) to express an experience curve by using an exponential regression depending

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on investment cost of new technology components $IC_{New\_t}(x)$, the learning index b and the investment cost of the first unit a:

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

III. ENERGETIC 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 balances and the fuel intensity in kWh/100km driven up to 2050.

Fig. 1 and Fig. 2 compare the well-to-tank (WTT) , tank-to-wheel (TTW) and WTW net CO_2 emissions of conventional and alternative vehicles powered by various energy sources in 2010 and 2050 for the average of EU-countries. A major perception of this figure is that despite BEV and FCV do not emit CO_2 in the TTW-chain they are ecologically unfavorable compared to conventional ICE vehicles if the electricity or hydrogen are generated in fossil power plants.

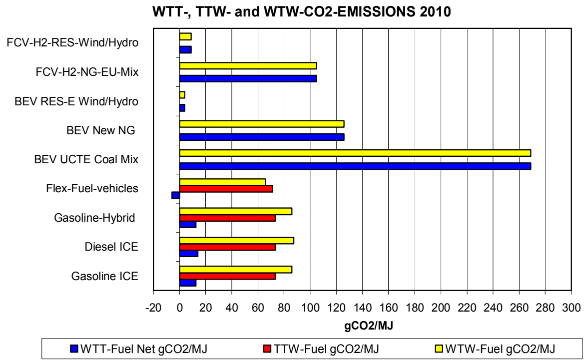

Figure 1. WTT-, TTW- and WTW net CO_2 emissions of various vehicles and energy sources in 2010 for the average of EU-15 countries.

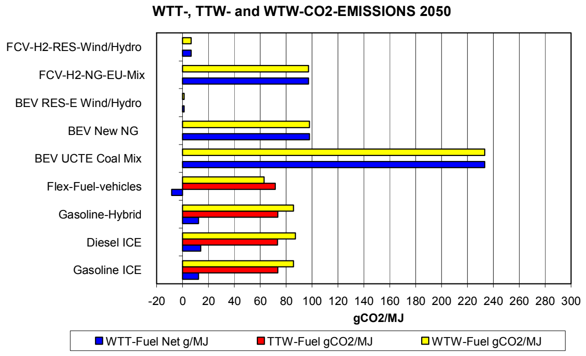

Figure 2. WTT-, TTW- and WTW net CO_2 emissions of various vehicles and energy sources in 2010 for the average of EU-15 countries.

Fig. 3 describes the expected historical developments of passenger cars' fuel intensities and assumptions for development in the business as usual (BAU) scenario up to 2050 (for average car size of 80 kW). Note that the steepest decrease in fuel intensities took already place before 2011 as a first result of the efforts of European commission to improve the efficiency of cars. For further details on life-cycle energy balances see [1].

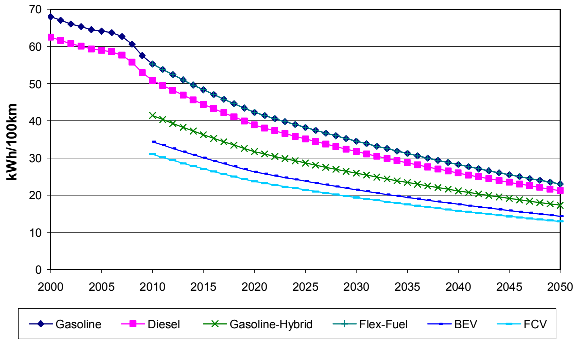

Figure 3. Historical developments of passenger cars' fuel intensities and assumptions for development in the BAU scenario up to 2050 (for average car size of 80 kW) (References: [3-7]).

IV. TECHNOLOGICAL LEARNING

Future production costs of alternative powertrains will be reduced through technological learning. Technological learning 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 $IC_{New\_t}(x)$.

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

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:

$$IC_{New_t}(x) = IC_{New_t}(x_{nat_t}) + IC_{New_t}(x_{int_t}) \qquad (6)$$

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 by using an exponential regression depending on learning index b and the investment cost of the first unit a.

In this paper we analyze possibilities of technological learning in future based on an ambitious scenario for world-wide market diffusion of the analyzed car types as depicted in Fig 4. Next we compare BEV and conventional cars in detail. Figures 5 and 6 show the developments of investment costs of the BEV and conventional powertrains over time considering technological learning and service increases in period 2010 - 2050. As Fig. 5 depicts even for conventional cars small technological learning effects are to be expected.

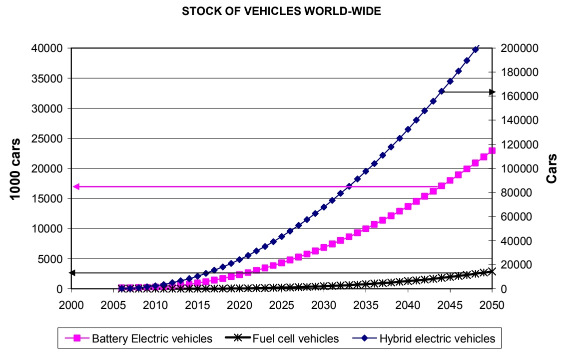

Figure 4. Over-all scenarios for world-wide wide market diffusion of HEV, BEV and FCV 2010 -2050.

And hence, also these cars should have 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 cost savings which have incurred for the "naked" car due to technological learning. This effect is depicted in detail for conventional cars in Fig. 5 and is also applied in Fig. 6 for BEV.

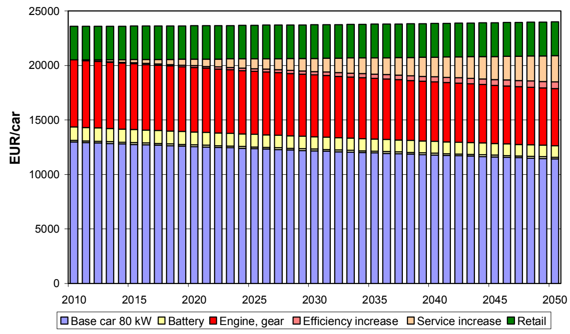

Figure 5. Development of car investment costs of conventional cars (80 kW) considering TL and service increases 2010 -2050.

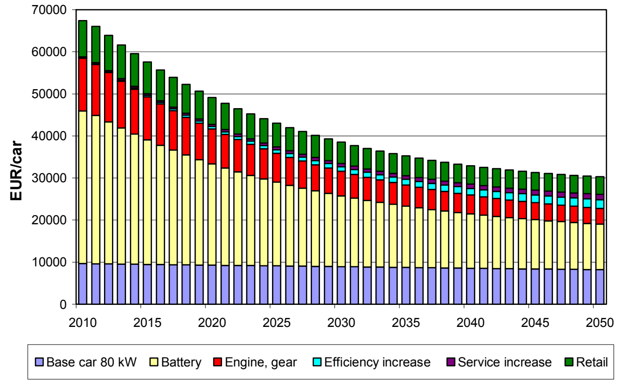

Figure 6. Development of car investment costs of BEV (80 kW) considering TL and service increases 2010 -2050.

In Figures 5 and 6 the technological learning effect is applied to the base car, the battery and the engine specific components. In addition costs occur for the over-all efficiency increases. The latter are revealed in better fuel intensities over time. Fig. 7 summarizes the IC developments of the considered powertrains for the period 2010 to 2050. Of course, the most remarkable cost decreases are expected for BEV and FCV.

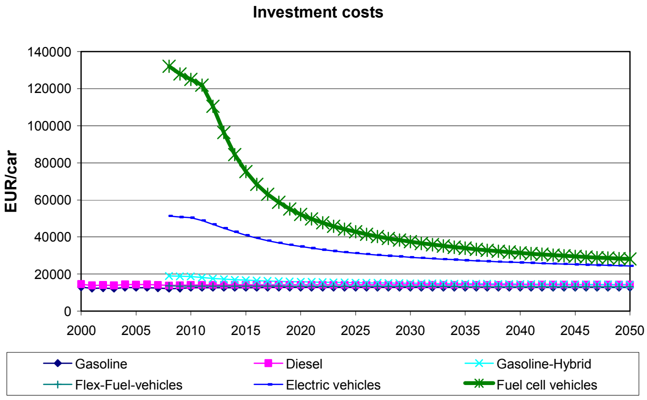

Figure 7. Development of investment costs of the considered powertrains over time considering TL and service increases 2010 -2050

V. 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. Our analysis starts with the fuel costs. Fig. 8 compares the scenarios for the development of the fuel costs (incl. taxes) of the service mobility per 100km driven from 2010 to 2050.

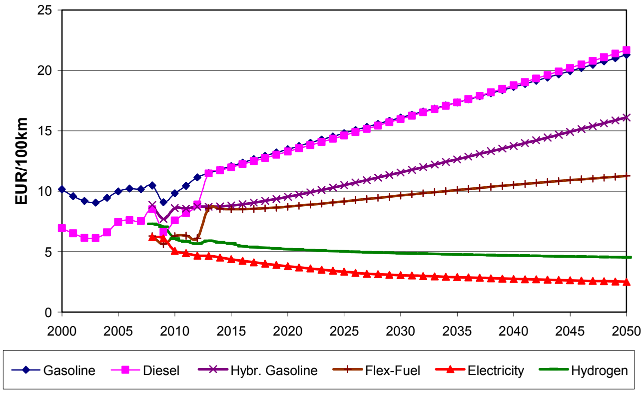

Figure 8. Scenario of fuel costs including taxes per 100 km, 2010 -2050.

In our scenario CO_2 taxes replace excise taxes in 2013 and increase up to 2050 by 1.5 cent/kg CO_2 and year. Fuel costs for driving remain cheapest for electricity but costs of hydrogen cars come closer and are remarkably cheaper than fossil fuels and biofuels, see Fig.8. Due to the introduced CO_2 taxes price increases are highest for the fossil fuel driven vehicles.

Figures 9 and 10 describe the cost structure of total costs of service mobility per 100km driven of different types of cars in 2010 and in 2050. We can see that the advantages of alternative powertrains regarding lower fuel costs are more than compensated by very high capital costs in 2010, see Fig. 9

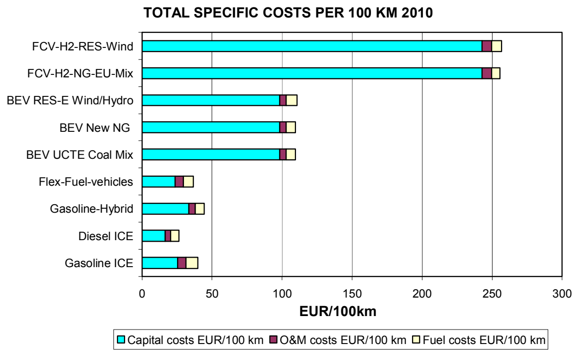

Figure 9. Total costs of service mobility per 100km driven in passenger cars in 2010.

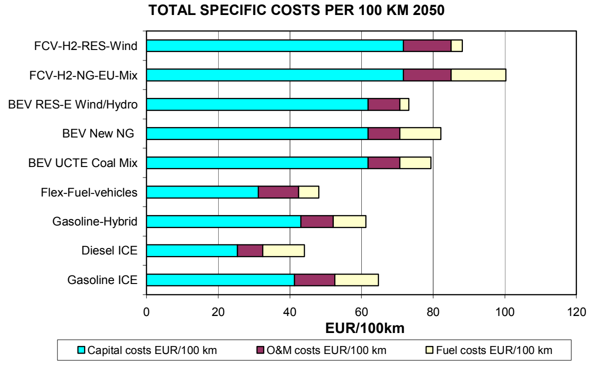

Figure 10. Total costs of service mobility per 100km driven in passenger cars in 2050.

The specific capital costs are the highest component of the driving costs for all alternative powertrains (and conventional cars as well). HEV, BEV and FCV take into account the actual costs for batteries as well as for fuel cells. However, these costs can be significantly reduced until 2020 based on technical improvement potentials, see Fig. 6. The total costs of most cars will almost even out by 2050, see Fig 10. Yet, diesel vehicles still remain cheapest option, mainly because of more kilometers driven, so capital costs are distributed to larger distances.

Fig.11 compares the development of the total costs of service mobility per 100km driven of different types of passenger cars from 2010 to 2050. We can see that total costs of mobility with conventional vehicles is continuously increasing – mainly because of the CO_2 taxes introduced and increases in fossil fuel costs – while driving costs of BEV and FCV decrease significantly. This is mainly due to technological learning that reduces costs of batteries and fuel cells.

A paradox aspect that can be seen from Fig. 11 is that economics of alternative powertrains is better with the increasing number of kilometers driven per car and year. This implies that on the one hand it is more favorable to substitute diesel cars by BEV and on the other hand it emphasizes the problem of the limited operating range.

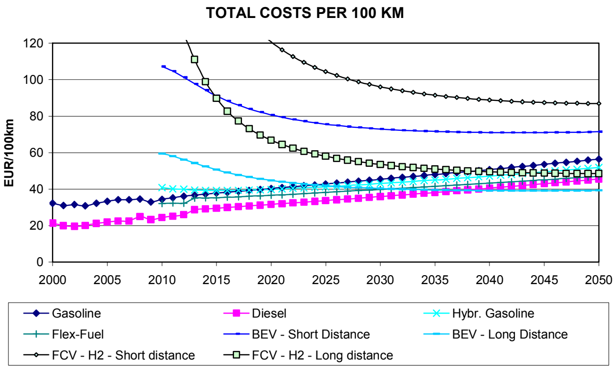

Figure 11. Development of total costs of service mobility per 100km driven of different types of passenger cars in 2000- 2050.

VI. CONCLUSIONS

The major conclusions of this analysis are: From a technical point of view BEV and FCV are currently clearly preferable to conventional ICE vehicles. They have better ecological performance as well as energetic conversion efficiency. Yet, this applies only if the electricity respectively the hydrogen used in the cars is produced from renewable energy sources.

With respect to the economic competitiveness of alternative powertrains compared to conventional vehicles in the most favorable case – long distance driven – BEV will enter the market by about 2025. FCV will become competitive even later, by about 2040. Also in this case optimistic assumptions are used in favor 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 it is to note that by 2050 the total overall driving costs of most analyzed 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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