Driving on Renewables—On the Prospects of Alternative Fuels up to 2050 From an Energetic Point-of-View in European Union Countries

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The core objective of this paper is to investigate the perspectives of "renewable fuels" mainly from an energetic point-of-view in a dynamic framework until 2050 in comparison to fossil fuels. In addition, the impact on the economic prospects of an improvement of the energetic performance is analyzed. As renewable fuels, various categories of first and second generation biofuels as well as electricity and hydrogen from renewable energy sources are considered. The most important results of this analysis are: (i) While for first generation biofuels, the relatively high share of fossil energy is the major problem, for second generation biofuels, the major problems are the low conversion efficiency and the corresponding high input of renewable feedstocks. Up to 2050, it is expected that these problems will be relieved, but only slightly. (ii) The energetic improvements up to 2050 will lead to substantial reduction of energetic losses in the well-to-tank as well as in the tank-to-wheel part of the energy service provision chain. (iii) By 2050, the total driving costs of all analyzed fuels and powertrains will almost even out. (iv) The major uncertainty for battery electric and fuel cell vehicles is how fast technological learning will take place especially for the battery and the fuel cells. [DOI: 10.1115/1.4023919]

Keywords: biofuels, renewables, electric vehicles, fuel cell vehicles, energetic performance, economics

1 Introduction

Fuels based on renewable energy are considered as a major environmentally benign alternative to fossil fuels in passenger car transport. However, the ecological performance, energetic balance, and finally, the high costs are still major barriers for a broad market breakthrough of these energy carriers.

The core objective of this paper is to investigate the perspectives of renewable fuels from an energetic point-of-view in a dynamic framework until 2050 in comparison to fossil fuels. Of specific interest in this context is to split up total energy of alternative fuels into a renewable (RE) and a fossil (FF) energy part based on a life-cycle assessment approach. In addition, the impact of the energetic performance on the future costs of "renewable fuels" (including CO_2-taxation) is investigated in an economic analysis. As renewable fuels, we consider various categories of first and second generation biofuels as well as electricity and hydrogen from renewable energy.

The analysis is conducted for the time period up to 2050 and is based on average figures for EU-15 countries regarding production of biofuels, conversion of biomass into fuels, electricity and hydrogen from biomass, wind, and hydro. We note that up to 2050 fundamental changes in the structure of passenger transport may also have taken place. However, these changes are not the subject of this paper and do not influence the results. Only in the case of learning rates used for the final economic analysis do we have to rely on an external scenario.

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2 Method of Approach

The energetic assessment is based on the analysis of the whole energy chain from primary energy resources until energy service mobility (see Fig. 1). The whole well-to wheel (WTW) chain, includes well-to-tank (WTT), and tank-to-wheel (TTW) parts.

Moreover, from an energetic point-of-view it is of interest to know how much fossil and renewable energy is used to provide a unit of energy to be used in the car. This is described by the primary energy or feedstock conversion factor f_{conv}. The overall energy used per kilometer driven resulting from conversion efficiency in the WTT- and the TTW-part of the chain is

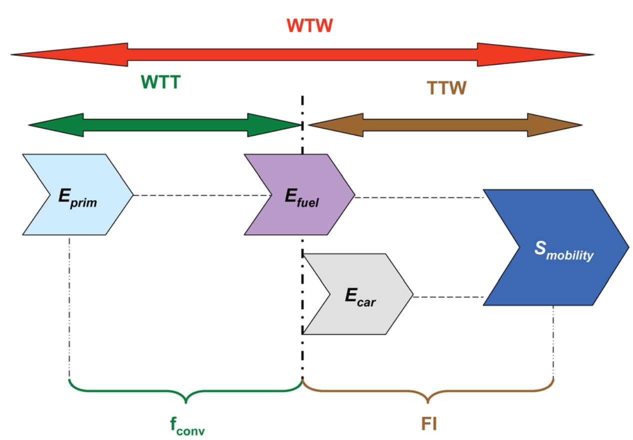

Fig. 1 WTT and TTW—conversion in the energy service providing chain

$$E_{\mathrm{WTW}} = E_{\mathrm{WTT}} + E_{\mathrm{TTW}} \tag{1}$$

$$E_{\mathrm{WTT}} = (f_{\mathrm{conv}} - 1)\mathrm{FI} \tag{2}$$

$$E_{\mathrm{TTW_{FF}}} = \mathrm{sh_{FF}FI} \tag{3}$$

$$E_{\mathrm{TTW_{RE}}} = \mathrm{sh_{RE}FI} \tag{4}$$

$$E_{\mathrm{WTT_{RE}}} = (f_{\mathrm{conv}} - 1)\mathrm{sh_{RE}FI} \tag{5}$$

$$E_{\mathrm{WTT_{FF}}} = (f_{\mathrm{conv}} - 1)\mathrm{sh_{FF}FI} \tag{6}$$

$$E_{\mathrm{RE_{LCA}}} = E_{\mathrm{RE_{LCA\_CAR}}} + E_{\mathrm{RE_{WTW}}} \tag{7}$$

$$E_{\mathrm{RE_{WTW}}} = f_{\mathrm{conv}}\mathrm{sh_{RE}FI} \tag{8}$$

$$E_{\mathrm{FF_{LCA}}} = E_{\mathrm{FF_{LCA\_CAR}}} + E_{\mathrm{FF_{WTW}}} \tag{9}$$

$$E_{\mathrm{FF_{WTW}}} = f_{\mathrm{conv}}\mathrm{sh_{FF}FI} \tag{10}$$

where f_{conv} is the conversion factor of feedstock (FS) or primary energy into fuel (kWh_FS/kWh_Fuel), FI is the fuel intensity (kWh_Fuel/100 km), $E_{\mathrm{RE_{LCA}}}$ is the total renewable energy used (kWh_FS/100 km), $E_{\mathrm{FF_{LCA}}}$ is the total fossil energy used (kWh_FS/100 km), $E_{\mathrm{RE_{LCA\_CAR}}}$ is the renewable energy used for production and scrappage of the car, $E_{\mathrm{FF_{LCA\_CAR}}}$ is the fossil energy used for production and scrappage of the car, $E_{\mathrm{RE_{WTW}}}$ is the total renewable energy used for production of fuel used, $E_{\mathrm{FF_{WTW}}}$ is the total fossil energy used for production of fuel used, $\mathrm{sh_{RE}}$ is the share of renewable energy in WTT-balance, and $\mathrm{sh_{FF}}$ is the share of fossil energy in WTT-balance.

We also consider the energy needed for construction and scrappage of the cars, see Eqs. (7) and (9). This energy is also divided in fossil energy ($E_{\mathrm{FF_{LCA\_CAR}}}$) and renewable energy ($E_{\mathrm{RE_{LCA\_CAR}}}$).

This work extends the analysis conducted in Ajanovic et al. [1–3]. The characteristics of alternative fuels and vehicles and their impacts on emissions reductions and energy consumptions are documented in a number of studies [4–8]. With respect to the literature, the most important analyses are summarized in CONCAWE reports [9,10] and Toro et al. [11].

In this paper, we compare different categories of alternative fuels to conventional fossil fuels. We focus on electricity and hydrogen from RES and the following categories of biofuels:

First generation biofuels:

- BD-1: biodiesel from rape seed and other oil seeds
- BE-1: bioethanol from wheat and maize
- BG: biogas—the term "biogas" in this paper refers to biomethane from manure, grass, and green maize

Second generation biofuels:

- BD-2: biodiesel from biomass-to liquids (BTL) with Fischer–Tropsch (FT) process
- BE-2: bioethanol from lignocellulose
- SNG: biogas from synthetic gas from biomass

The dynamic economic analysis up to 2050 is based on three categories of assumptions:

- Increases in fossil fuel prices are based on expected price developments as documented by the International Energy Agency (IEA) [12] and our own analyses for feedstock prices and wood-based resources in EU-27. In this scenario, we assume price increases for fossil fuels of 3% per year up to 2050, of 2% per year for feedstocks (oil seeds, cereals), and 1% per year for wood-based resources[1].
- The introduction of a CO_2 based tax starting from 2013, as described later in detail in Sec. 6.
- The dynamic analyses of the investment costs of alternative fuels and alternative automotive systems are based on international learning rates for the corresponding investments. These learning rates are based on international quantities. The data used for this report—especially for the estimation of the effects on technological learning[2]—are based mainly on studies of the IEA. The major assumptions regarding technological learning effects used for the scenario analysis are:
  - (i) The development is based on international learning rate of 25% and national learning rate of 15% regarding the investment costs of considered technologies.
  - (ii) International learning corresponds to worldwide quantity developments as documented in the IEA "Blue Map" scenarios [17].

The basic data for 2010 used as starting values for the economic analysis are documented in Tables 3 and 4, see the Appendix. The investment costs of cars are calculated for the average of EU-15 using data from ACEA [18] and EUROSTAT [19] as well as from our own analyses of market prices. The average kilometers driven are based on the ALTER-MOTIVE- [20] and ODYSSEE-database [21].

For 2050 the investment costs are derived from technological learning effects due to larger quantities produced. Yet, technological learning takes place mainly for battery electric vehicles (BEV) and fuel cell vehicles (FCV). For conventional cars, these learning effects are almost fully exhausted or compensated with increases in services.

The average fuel costs, with and without taxes, for EU-15 in 2010 are documented in Table 2, see the Appendix. For 2050, they are obtained from the described increases in net fuel prices (excluding taxes) as well as the assumed switch from current excise taxes to a CO_2-based tax, see also Sec. 6. The major argument for a switch from excise taxes to CO_2-based taxes is that it is the most elegant way to provide equal conditions for all fuels, including alternative fuels, regarding their environmental effects.

3 Dynamic Energetic Well-to-Tank Assessment

From the energetic point-of-view, it is of course of interest what this performance looks like currently, what will be the range of possible developments, and under which conditions will developments take place and which ones.

The WTT analyses are based on the method of life cycle assessment (LCA). LCA was performed with the Global Emission Model of Integrated Systems (GEMIS), version 4.5 [22] done by Joanneum Research in scope of the project ALTETRÄ [23].

Figures 2, 3, and 4 depict how the conversion factor looks currently and what are the possible developments up to 2050. The starting points are depicted in Figs. 2, 3, and 4 on the left-hand side and in Tables 1 and 2. Figure 2 provides the energetic WTT assessment of the considered conventional fossil fuels and biofuels for 2010. We can see that a major problem of BF-1 is the relatively high share of fossil energy—higher than those of BF-2—while for BF-2 the low conversion efficiency and the corresponding high input of renewable feedstocks is the major problem. However, we can also see that up to 2050, it is expected that this problem will be relieved but only slightly.

[1]The price increases for feedstocks and wood-based resources are derived from the average price increases over the last ten years, 2000–2010. However, if the demand for wood increases considerably, higher price increases may also take place.

[2]Technological learning works as follows: For many products and services, unit costs decrease with increasing experience. The idealized pattern describing this kind of technological progress is referred as a learning curve, progress curve, experience curve, or learning by doing [13–15]. In its most common formulation, unit costs decrease by a constant percentage, called the learning rate, for each doubling of experience [16].

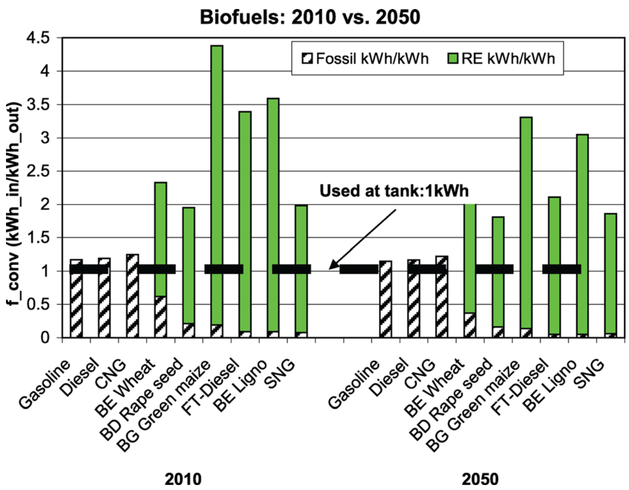

Fig. 2 The feedstock/fuel conversion factor f_{conv} for an energetic WTT assessment of conventional- and bio-fuels for 2010 and 2050 (data sources: Refs. [9,23])

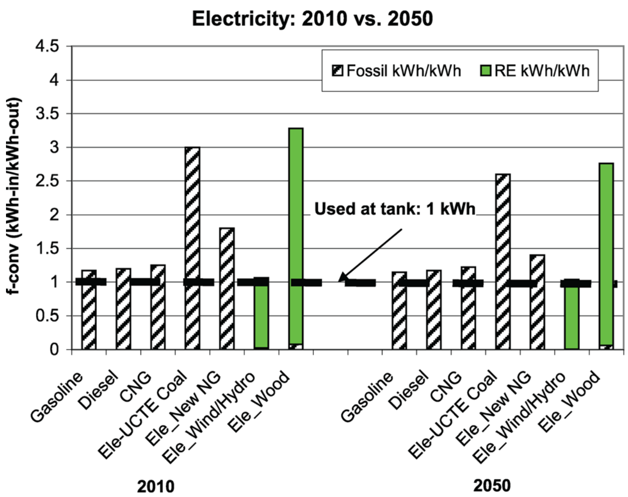

Fig. 3 Conversion factor f_{conv} for an energetic WTT assessment of conventional fuels and electricity for 2010 and 2050 (data sources: Refs. [9,23])

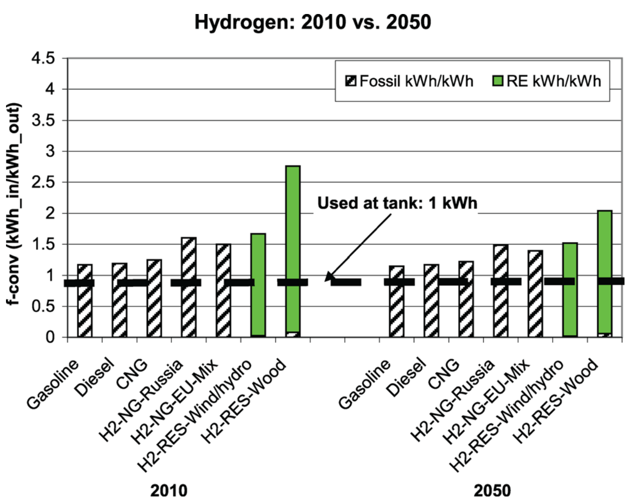

Fig. 4 Conversion factor f_{conv} for an energetic WTT assessment of conventional fuels and hydrogen for 2010 and 2050 (data sources: Refs. [9,23])

Table 1 WTT-conversion factor split up into a fossil and a renewable part for conventional and alternative fuels for 2010 (data sources: Refs. [9,23])

	Unit	FF input kWh/kWh	RE input kWh/kWh	Energy content kWh/unit
Gasoline	l gasol	1.17	0.00	8.70
Diesel	l diesel	1.19	0.00	9.96
CNG	kg CNG	1.25	0.00	12.53
LPG	kg LPG	1.12	0.00	12.78
Bioethanol wheat	l gasol_equ	0.62	1.71	8.70
Biodiesel RME	l diesel_equ	0.21	1.74	9.96
Biogas car	kg CNG	0.19	4.19	12.53
BTL-FT-diesel	l diesel_equ	0.09	3.31	9.96
Bioethanol Ligno	l gasol_equ	0.09	3.50	8.70
SNG	kg CNG_equ	0.08	1.90	12.53
Ele UCTE coal mix	kWh	3.00	0.00	1.00
Ele New NG	kWh	1.80	0.00	1.00
Ele RES-E wind/hydro	kWh	0.02	1.04	1.00
Ele RES-E wood	kWh	0.08	3.20	1.00
H_2-NG-Russia	kg H_2	1.60	0.00	33.36
H_2-NG-EU-mix	kg H_2	1.50	0.00	33.36
H_2-RES-wind/hydro	kg H_2	0.03	1.64	33.36
H_2-RES-wood	kg H_2	0.08	2.68	33.36

Table 2 WTT-conversion factor split up into fossil and renewable part for conventional and alternative fuels for 2050 (data sources: Refs. [9,23])

	Unit	FF input kWh/kWh	RE input kWh/kWh	Energy content kWh/unit
Gasoline	l gasol	1.15	0.00	8.70
Diesel	l diesel	1.17	0.00	9.96
CNG	kg CNG	1.22	0.00	12.53
LPG	kg LPG	1.10	0.00	12.78
Bioethanol wheat	l gasol_equ	0.37	1.71	8.70
Biodiesel RME	l diesel_equ	0.16	1.65	9.96
Biogas car	kg CNG	0.14	3.17	12.53
BTL-FT-diesel	l diesel_equ	0.05	2.06	9.96
Bioethanol Ligno	l gasol_equ	0.05	3.00	8.70
SNG	kg CNG_equ	0.06	1.80	12.53
Ele UCTE coal mix	kWh	2.60	0.00	1.00
Ele new NG	kWh	1.40	0.00	1.00
Ele RES-E wind/hydro	kWh	0.01	1.03	1.00
Ele RES-E wood	kWh	0.06	2.70	1.00
H_2-NG-Russia	kg H_2	1.48	0.00	33.36
H_2-NG-EU-mix	kg H_2	1.39	0.00	33.36
H_2-RES-wind/hydro	kg H_2	0.02	1.50	33.36
H_2-RES-wood	kg H_2	0.06	1.98	33.36

The conversion factor f_{conv} for an energetic WTT assessment of conventional fuels and electricity for 2010 and 2050 is depicted in Fig. 3. This figure depicts the clear preference for generating electricity from wind or hydro power.

Figure 4 depicts the conversion factor f_{conv} for an energetic WTT assessment of conventional fuels and hydrogen for 2010 and 2050.

A major indication of Figs. 3 and 4 is the high input required for producing electricity or hydrogen from biomass, which decreases only slightly up to 2050.

The WTT-conversion factors for fossil fuels, biofuels, electricity, and hydrogen are documented in detail in Tables 1 and 2, respectively, for 2010 and 2050.

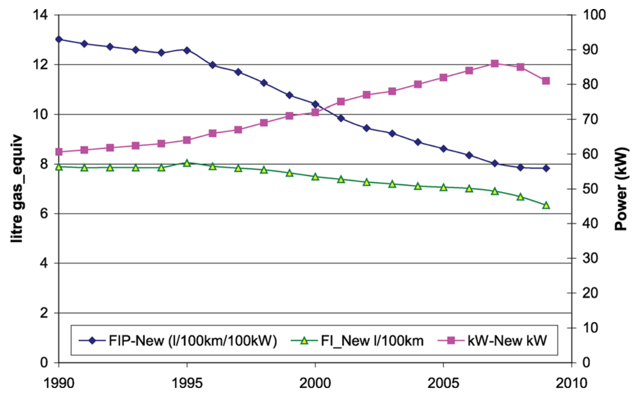

Fig. 5 Development of fuel intensity, power-specific fuel intensity, and power (kW) of new vehicles in EU-15 from 1990 to 2009 [26,27]

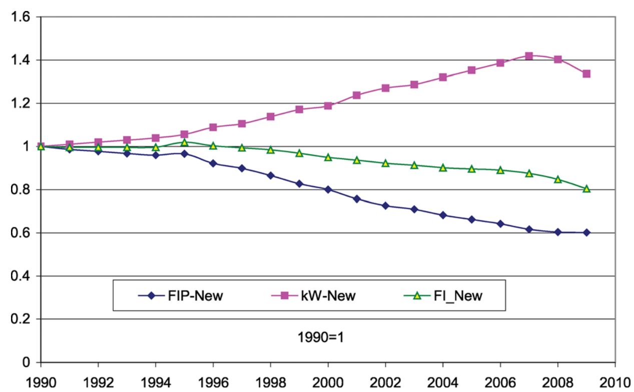

Fig. 6 Normalized development (1990 = 1) of fuel intensity, power-specific fuel intensity, and power of new vehicles in EU-15 from 1990 to 2009 [26,27]

4 Tank-to-Wheel Analysis: Development of Fuel Intensity

The size of the cars is a very important impact factor in terms of energy consumption. In EU-15 countries, the average power of passenger cars has increased from about 60 kW in 1990 to more than 80 kW in recent years, see Fig. 5. This figure also shows the development of fuel intensity (FI) and a power-specific fuel intensity of new vehicles in EU-15 from 1990 to 2009. The fuel intensity in Figs. 5 and 6 does not reflect the real efficiency improvement because it is distorted by the switch to larger cars. To correct for this, we define power-specific fuel intensity (FIP):

$$\mathrm{FIP} = \frac{\mathrm{FI}}{P}\ (\mathrm{l}/(100\ \mathrm{km\,kW})) \tag{11}$$

As it can clearly be seen from Figs. 5 and 6, the decrease in FIP from 1990 to 2009 was virtually twice as high as the decrease of FI. Hence, the switch to larger cars has reduced the possible savings due to efficiency improvements by about 50%, see also Ajanovic et al. [24].

The historical developments of passenger cars' fuel intensities and assumptions for future development up to 2050 (for average car size of 80 kW) are described in Fig. 7. The steepest decrease in fuel intensities already took place before 2011 as a result of European policy efforts regarding the improvements of the efficiency of cars. The decreases in Fig. 7 up to 2050 are based on possible technical improvements as described in detail in Ajanovic and Haas [25] based on the literature [9–11,26–29].

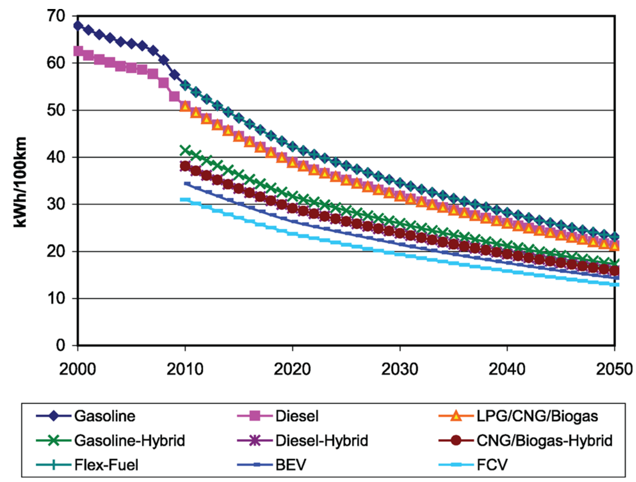

Fig. 7 Historical developments of passenger cars' fuel intensities and assumptions for future development up to 2050 (for average car size of 80 kW) (data source: Refs. [9–11,26–29])

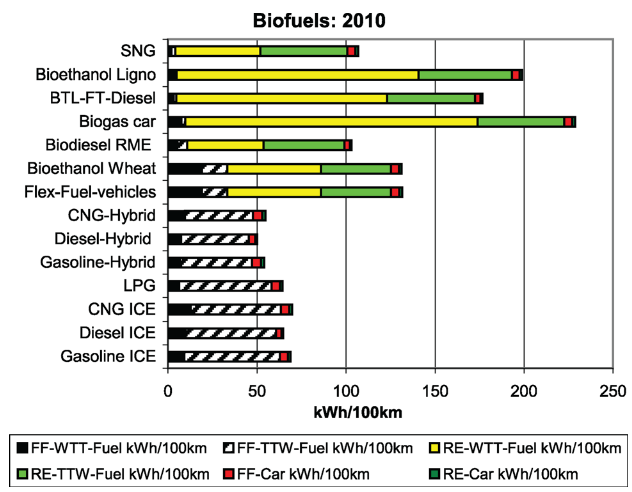

Fig. 8 Renewable and fossil energy shares in the whole WTW energy service provision chain in 2010 for conventional fuels versus biofuels

5 Summary: Aggregated Well-to-Wheel Analysis

In this section, an aggregated well-to-wheel assessment is conducted linking the WTT and TTW analysis presented in Secs. 3 and 4.

For conventional fuels and biofuels, the renewable and fossil shares in the whole WTW energy service provision chain for 2010 are depicted in Fig. 8. We can see that for all biofuels large parts of the total energy balance are attributed to WTT conversion losses.

The corresponding comparison for 2050 is illustrated in Fig. 9. It depicts the renewable and fossil energy shares in the whole WTW energy service provision chain for conventional fuels versus biofuels for 2050. Due to better fuel intensity, the energy balance is improved for virtually all fuels compared to 2010. The improvements in the WTT-part are especially remarkable for biofuels second generation.

For electricity and hydrogen used in BEV and FCV, the renewable and fossil shares in the whole WTW energy service provision chain are shown in comparison to conventional fuels in Fig. 10 for 2010. It can be seen that considering the whole WTW chain the advantage of driving on electric renewables is clearly higher for electricity from wind or hydro than from biomass. In total, the advantages of BEV and FCV are rather small.

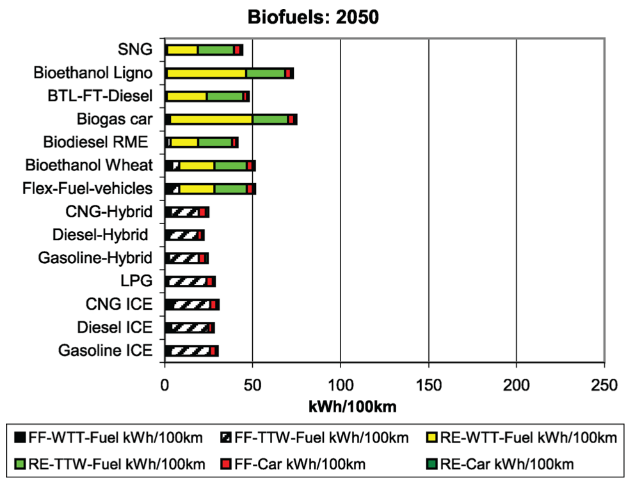

Fig. 9 Renewable and fossil energy shares in the whole WTW energy service provision chain in 2050 for conventional versus biofuels

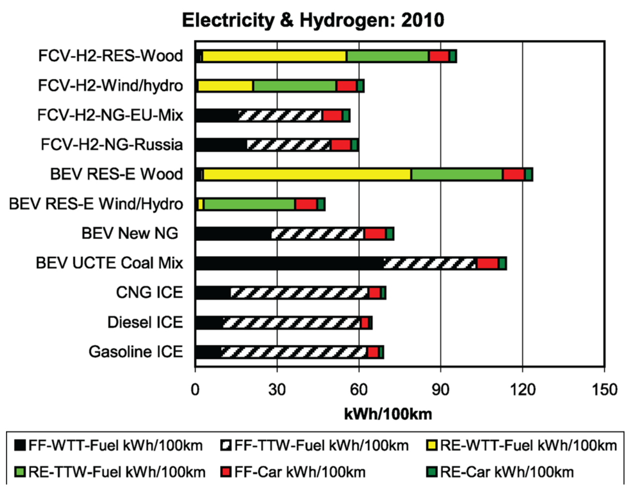

Fig. 10 Renewable and fossil energy shares in the whole WTW energy service provision chain in 2010 for conventional fuels versus fuels used in BEV and FCV

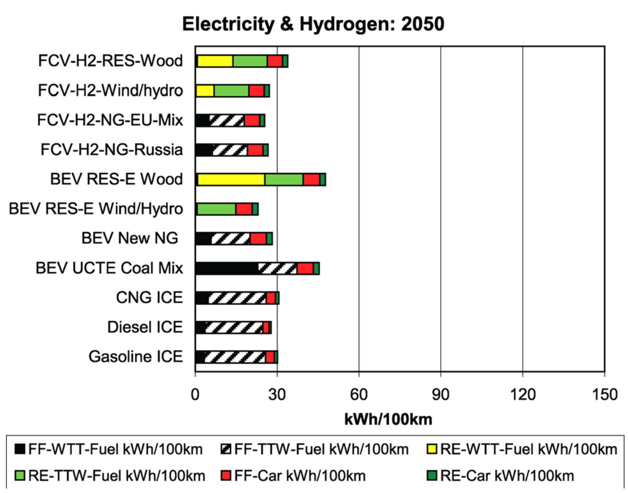

Fig. 11 Renewable and fossil energy shares in the WTW energy service provision chain in 2050 for conventional fuels versus fuels used in BEV and FCV

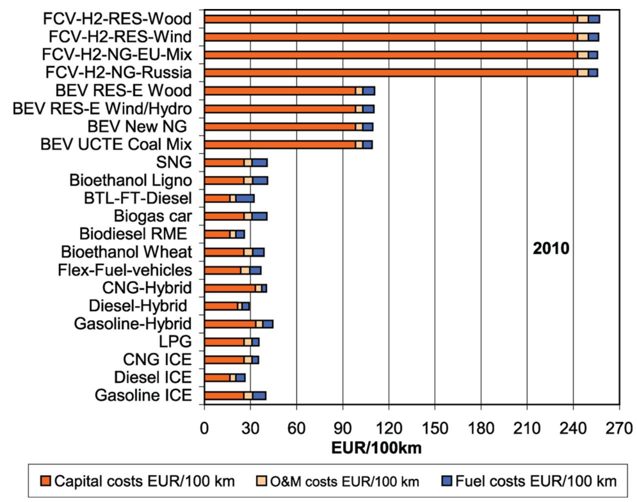

Fig. 12 Total costs of service mobility in passenger cars in 2010

Figure 11 depicts the renewable and fossil energy shares in the whole WTW energy service provision chain for conventional fuels versus fuels in BEV and FCV for 2050. Compared to 2010, fuel cell vehicles show the best improvement of performance mainly due to better fuel intensity.

6 Economic Assessment

Of special interest in this analysis is, finally, how improvements in energetic performance influence economic competitiveness. The basic framework for the economic assessment is explained in detail in Ajanovic and Haas [2], and Ajanovic et al. [26]. The major results relevant for this paper are presented in this section.

The major assumption in this analysis is a fuel tax reform. We have assumed that the highest excise tax in 2010—which was on gasoline—is converted to a CO_2 based tax of the same magnitude. For all other fuels, including alternative fuels, this tax is set relative to their WTW-CO_2 emissions compared to gasoline. CO_2 based tax starts in 2013 and is increased by 0.015 EUR/kgCO_2/yr up to 2050. Due to this tax, alternative fuels with lower CO_2 balances also have lower tax levels.

The advantages of BEV and FCV regarding lower fuel costs are more than compensated by higher capital costs in 2010, see Fig. 12. By 2050 costs of most cars will even out, see Fig. 13.

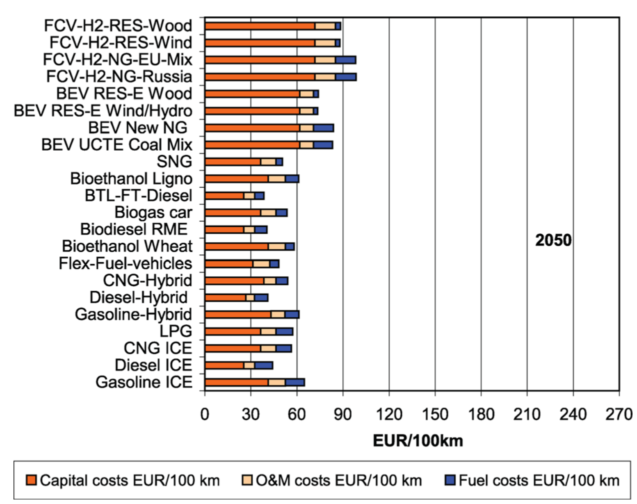

Fig. 13 Total costs of service mobility in passenger cars in 2050

Yet, various diesel cars still remain cheapest, mainly because of more km driven in these cars and distribution of capital costs to larger distances.

7 Conclusions

The major conclusions of this analysis are:

The energetic improvements of all powertrains up to 2050 will lead to a substantial reduction of losses in the WTT as well as in the TTW part of the energy service provision chain. However, from our analysis, it is likely that more significant improvements take place in the TTW part. For second generation biofuels and biogas, significant efficiency improvement potentials exist in the whole chain. Yet, for all biofuels as well as for the use of biomass for electricity generation and hydrogen production, the problem remains that the conversion factor in 2050 is still expected to be rather high, between 2 and 3, see Figs. 2, 3 and 4.

Regarding the expected improvements of the fuel intensity in the TTW part, it is important to state that savings in overall fossil energy consumption may not fully be harvested because of service becoming cheaper. Another important issue is the size of cars. As shown in this paper, increasing power of cars may considerably reduce technical efficiency improvements (see also Ajanovic et al. [24]).

With respect to the economic performance, the major perception for 2050 is that the described energetic improvements in the WTW chain and the expected learning effects, especially for BEV and FCV, will lead to a tighter range of overall costs of all investigates renewable fuels and alternative automotive technologies.

Finally, the following major uncertainties remain: (i) how soon and to what extent will BEV and FCV enter the market; (ii) how fast will technological learning take place especially for the battery and the fuel cells, and (iii) how will consumers behavior change with respect to size of cars purchased and with respect to vehicle kilometers driven?

Nomenclature

BD-1 = biodiesel from rape seed and other oil seeds
BD-2 = biodiesel from biomass-to liquids with Fischer–Tropsch process
BE-1 = bioethanol from wheat and maize
BE-2 = bioethanol from lignocellulose
BF-1 = first generation biofuels
BF-2 = second generation biofuels
BTL = biomass to liquids
BG = biogas—the term "biogas" in this paper refers to biomethane from manure, grass, and green maize
CNG = compressed natural gas
FF = fossil energy
FI = fuel intensity
FIP = power-specific fuel intensity
FT = Fischer–Tropsch process
H_2 = hydrogen
ICE = internal combustion engine
LCA = life cycle assessment
LPG = liquefied petroleum gas
NG = natural gas
P = power
RE = renewable energy
RES = renewable energy sources
RME = rapeseed methyl ester
SNG = biogas from synthetic gas from biomass
TTW = tank-to-wheel
WTW = well-to-wheel
WTT = well-to-tank
BEV = battery electric vehicles
FCV = fuel cell vehicles

Appendix

Table 3 Car-specific data for 2010 (sources: Refs. [18,20,26])

	2010		
	Investment costs EUR/car	O&M costs EUR/car/yr	Distance driven km/year
Gasoline ICE	17,335	624	10,499
Diesel ICE	17,919	624	16,663
CNG/LPG ICE	17,427	550	10,483
Gasoline-hybrid	22,635	499	10,499
Diesel-hybrid	23,219	499	16,663
CNG-hybrid	22,427	440	10,483
Flex-fuel-vehicles	16,008	624	10,499
BEV	50,868	374	8000
FCV	125,500	562	8000

Table 4 Fuel costs for 2010 (sources: Refs. [23,30])

		2010	
		Incl. tax	Excl. tax
Fuel	Unit	EUR/unit	EUR/unit
Gasoline	EUR/l gasoline	1.35	0.56
Diesel	EUR/l diesel	1.18	0.65
CNG	EUR/kg CNG	1.00	0.75
LPG	EUR/kg LPG	1.10	0.83
Bioethanol wheat	EUR/l BE	0.79	0.65
Biodiesel RME	EUR/l biodiesel	1.05	0.86
Biogas	EUR/kg biogas	1.47	1.22
BTL-FT-diesel	EUR/l biodiesel	2.17	1.81
Bioethanol Lignocell.	EUR/l BE	1.15	0.96
SNG	EUR/kg SNG	1.72	1.43
Electricity from new NG power plant	EUR/kWh	0.19	0.13
Electricity from wind/hydro	EUR/kWh	0.20	0.14
Electricity from wood	EUR/kWh	0.22	0.16
H_2 from NG from Russia	EUR/kg H_2	7.36	6.13
H_2 from NG-EU-mix	EUR/kg H_2	7.36	6.13
H_2 wind/hydro	EUR/kg H_2	7.94	6.62
H_2 from wood	EUR/kg H_2	8.73	7.27

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