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Renewable fuels – A comparative assessment from economic, energetic and ecological point-of-view up to 2050 in EU-countries

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Fuels based on renewable energy sources (RES) such as a variety of first and second generation biofuels as well as electricity and hydrogen from RES, are considered an important means of coping with the environmental problems of transport. The objective of this paper is to investigate the “renewable fuels” from economic, energetic and ecological perspective within a dynamic framework until 2050.

The key results show that all fuels analysed have lower CO_2 emissions than gasoline, but drawbacks include the high costs of hydrogen- and electricity-driven vehicles. By 2050 however these costs could be reduced due to technological learning effects and efficient policy measures (e.g. CO_2-based tax). We conclude that “renewable fuels” will only play a significant role if CO_2 taxes, intensified R&D and technological learning are strategically implemented.

1. Introduction

In recent years the major challenges for EU climate and energy policy have been to implement effective policies and measures to mitigate global warming, improve air quality and reduce energy consumption. Since about one quarter of EU greenhouse gas emissions comes from the transport sector, a significant number of EU measures for reducing CO_2 emissions are directed to this sector with renewable fuels playing an important role. According to EU “20–20–20 targets”, by 2020 at least 10% of fuels used in transport should come from RES [1,2].

Transport is the fastest growing sector in terms of energy use. It plays a central role in the European economy and accounts for almost 20% of the total gross energy consumption in Europe. 98% of the energy consumed in this sector is fossil energy [3]. The European Commission has recognized this problem, see e.g. a White paper "Roadmap to a Single European Transport Area – Towards a competitive and resource efficient transport system”, [4].

How this will develop in the future depends on technological progress and policy measures implemented. The environmental, economic and energetic benefits of alternative fuels have been discussed in numerous scientific papers. Important contribution to literature have been provided by Huo et al. [5] who focus on a life-cycle assessment of energy use and GHG emissions from biodiesel. The environmental, economic and energetic benefits of biodiesel and bioethanol are discussed by Hill et al. [6]. Hydrogen as a renewable fuel for a transport is analysed by Specht et al. [7] and Ajanovic [8]. Biofuels have been compared with electricity and hydrogen from biomass by Ohlrogge et al. [9] and Campbell et al. [10].

In this paper we analyse and compare all relevant renewable fuels, biofuels and RES-based electricity and hydrogen.

The most important renewable fuels in the EU today are the first generation biofuels, biodiesel and bioethanol. They are however, often criticized due to the relatively bad ecological performance and their competition with food production. Currently there are higher expectations of second generation biofuels which can be produced using different kind of lignocellulosic materials, as well as from RES-based electricity and hydrogen.

The objective of this paper is to investigate the “renewable fuels” from economic, energetic and ecological points of view in a dynamic framework until 2050 in EU-countries. A comparison has been conducted of selected fuels, as well as of total energy service provided by these fuels, (see Fig. 1). The three categories of “renewable” fuels investigated are: biofuels, and RES-based electricity and hydrogen.

Biofuels:

The following three types of biofuels have been analysed for 2010:

- first generation biodiesel produced from rapeseed methyl ester (RME);

Abbreviations: FT-Diesel, Fischer–Tropsch diesel; GHG, greenhouse gas; H2, hydrogen; ICE, internal combustion engine; LCA, life cycle assessment; PV, photovoltaic; RES, renewable energy sources; R&D, research and development; RME, rapeseed methyl ester; SNG, synthetic natural gas; TTW, tank-to-wheel; VAT, value added tax; WTT, well-to-tank; WTW, well-to-wheel.

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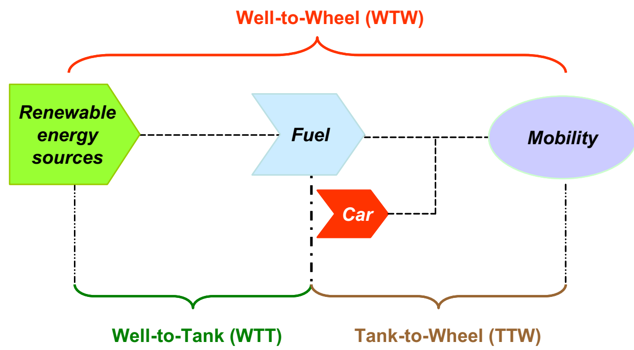

Fig. 1. The energy chain for providing the service mobility (based on [12]).

- first generation bioethanol produced from wheat or corn;
- biogas produced from organic waste, maize silage or grass.

For 2050 the following three types of second generation biofuels have been analysed:

- second generation biodiesel, Fischer–Tropsch (FT) diesel;
- second generation bioethanol produced from different types of lignocellulosic resources;
- synthetic natural gas (SNG).

Electricity:

Three types of RES-electricity have been analysed for 2010 and 2050:

- electricity produced from wind or hydro power: these two sources are treated together as they have virtually the same ecological and economic performance;
- electricity from photovoltaics (PV);
- electricity produced from biomass in combustion plants.

Hydrogen:

Three types of hydrogen have been analysed for 2010 and 2050:

- hydrogen produced from wind or hydro power by electrolysis: again these two sources are treated together as their ecological and economic performance is virtually identic;
- hydrogen produced from PV by electrolysis;
- hydrogen from biomass produced by means of steam reforming.

Currently the most common fuel for cars in Europe is gasoline. However, over the last two decades there has been a continued increase in the use of diesel. Diesel vehicles shown a higher engine efficiency and hence lower CO_2 emissions as reported in literature, e.g. Refs. [11,12]. However, the differences between gasoline and diesel are negligible with regard to economic, ecological and energetic considerations of renewable fuels and alternative automotive technologies. Since the major focus of this paper is on renewable fuels, gasoline has been selected as the comparison fuel.

2. Environmental and energetic assessment

The environmental and energetic assessment in this paper is based on the Life Cycle Assessment (LCA) method. Since the future use of renewable fuels depends on the key features of the energy service provided, the WTW analysis of the complete energy chain is given in addition to WTT analysis of fuels. The calculation of WTW CO_2 emissions is based on the following equation:

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

CO_2 emissions from biomass used for energy service are balanced zero according to IPCC [13] guidelines. This is based on the assumption that the balance of net CO_2 fixation of biomass by photosynthesis and the CO_2 emissions during production and conversion of the fuel is zero. In LCA, CO_2-fixation is considered as negative CO_2 emission during agricultural production. Carbon losses in fuel production processes (e.g. carbon in press cake from rapeseed pressing) are accounted for biogenic CO_2 emissions [14]. The LCA was performed in the scope of the project ALTETRÄ with the Global Emission Model of Integrated Systems (GEMIS), version 4.5 [15]. The cumulated primary energy demand (E_{WTW}) has been divided in total fossil energy (E_{FE}) and renewable energy (E_{RE}) demand:

$$E_{WTW} = E_{RE} + E_{FE} \tag{2}$$

This energy demand includes all energy input which is needed to deliver fuel to cars as well as the energy needed for car production and scrappage.

2.1. Greenhouse gas emissions

Fig. 2 shows the WTW CO_2 emissions of different renewable fuels compared to a conventional mobility chain with a gasoline fuelled internal combustion engine (ICE) vehicle which has been chosen as a reference system.

As seen in Fig. 2 all renewable fuels have lower WTW emissions per km driven compared to the fossil reference system. However, the results are very different depending on the fuel as well as on the primary energy sources used for the fuel's production.

The fuels analysed have been divided in three groups: biofuels, electricity and hydrogen.

Biomass-based fuels generally have negative WTT emissions, due to CO_2 fixation during photosynthesis. Negative WTT emissions are also related to non-energy co-products of the renewable fuels system which are used instead of conventional products and thus avoid related GHG emissions. Another contribution to WTT emissions are processes providing auxiliary energy and materials in biofuel production facilities. Relatively high WTT emissions for bioethanol production from wheat result mainly from the electricity and process heat required in the ethanol plant and its distillation unit [14].

WTT emissions of electricity from hydro and wind power are very similar and hence have been analysed jointly. Electricity from PV has higher WTT emissions due to the more energy-intensive production process of PV modules as well as relatively low

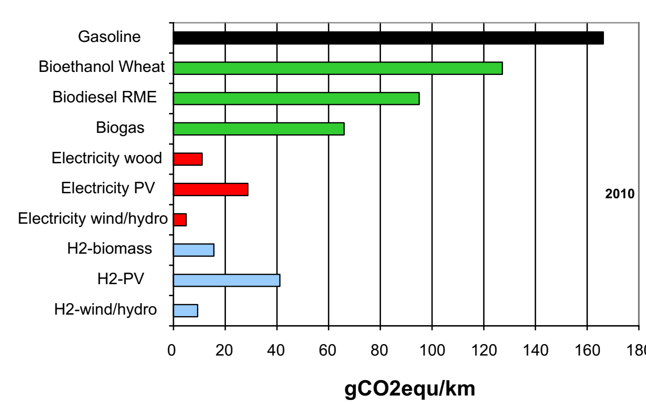

Fig. 2. Comparison of specific WTW CO_2 emissions in 2010 [14].

number of sunshine hours in Europe. WTT emissions for electricity from biomass can be considered of a negative value as it is assumed that the co-product is used for heat production in conventional biomass heating plants, thereby avoiding related life-cycle GHG emissions. TTW emissions also include those arising from the production, operation and disposal of cars.

WTW emissions of hydrogen from renewable energy sources are also shown in Fig. 2. They include hydrogen production processes (electrolysis or biomass gasification) and hydrogen compression for vehicle fuelling. TTW emissions include those from production, operation and disposal of the fuel-cell vehicle and are the same for all hydrogen chains analysed. As seen in Fig. 2 the lowest WTW emissions are those of hydrogen produced by electrolysis with hydro or wind power.

By 2050 WTW emissions of all fuels analysed should be lower than in 2010, (see Fig.3). It is expected that biomass and biofuel production processes as well as the cars themselves will be more efficient in the future. By 2050 the second generation biofuels should become more competitive on the market and, due to better WTW CO_2 balances, should replace first generation biofuels to a large extent, especially bioethanol. Wood-based FT-Diesel and SNG have been shown to have the lowest WTW emissions compared to the other biofuels. These biofuels require relatively low energy and material input to the collection of the wood, for biofuel production plants and their gasification units [14].

Although internal combustion engine vehicles are already a mature technology, a significant technical improvement potential still exists regarding fuel intensity. Vehicle fuel efficiency could be increased through improved vehicle technologies such as variable valve timing and lift, cylinder deactivation, turbochargers, idle stop, direct fuel injection, variable compression ratio, continuously variable transmissions, automated manual transmissions, etc. [16]. These measures could contribute to a major reduction in CO_2 emissions of conventional gasoline cars by 2050.

2.2. Cumulative primary energy demand

The overall energy consumption per km driven depends on the conversion efficiency in the WTT and TTW section of the energy chain. Fig. 4 shows the cumulative primary energy demand of different renewable fuels compared to the fossil reference systems. All renewable fuels reduce the cumulative fossil primary energy demand but in most cases the total energy requirement is still higher than in case of the fossil reference system.

However, results vary depending on the kind of renewable fuel as well as the primary energy sources used for fuel production. Among the fuels analysed, those based on biomass have the highest cumulative primary energy demand. In 2010 wheat-based bioethanol revealed a relatively high WTW fossil cumulative primary energy demand with its production requiring large amounts of electricity and heat.

As shown in Fig.5, the scenario for 2050 shows an improved energy balance for all fuels due to better fuel intensity. The WTT energy balances could be significantly enhanced through the switch to second generation biofuels. The WTW cumulative primary energy demand in 2050 is lower than in 2010 for all fuels analysed (compare Figs. 4 and 5).

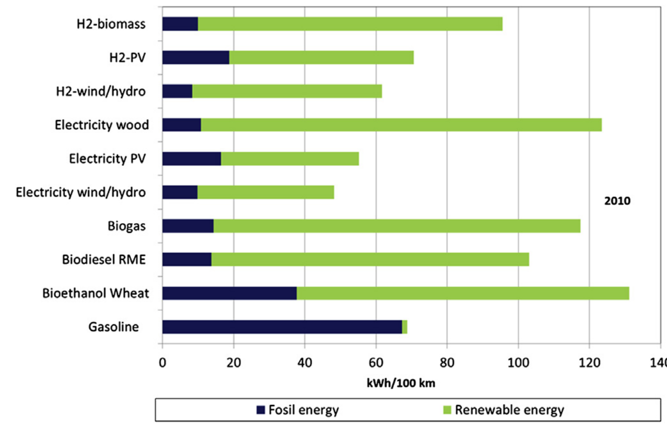

Fig. 4. Renewable and fossil energy distribution in the WTW energy service provision chain for gasoline versus renewable fuels [12], 2010.

3. Economic assessment

To market renewable fuels and alternative automotive technologies, it is important that they are economically competitive with conventional ICE vehicles and fossil fuels. In this paper the economic assessment of the future costs of mobility with different fuels and technologies is based on hypotheses derived from the Policy Scenario of the International Energy Agency [17]. In this context we have considered the following major impact parameters: (i) possible developments in the price of energy; (ii) global developments particularly regarding technological learning; and (iii) both the existing and planned energy and environment policies at the EU level. (For further details on scenario assumptions see ALTER-MOTIVE Final Report [11]). Our analysis is based on Ajanovic et al. [11–13,18]. (See references for the details of the formal economic and ecological framework.)

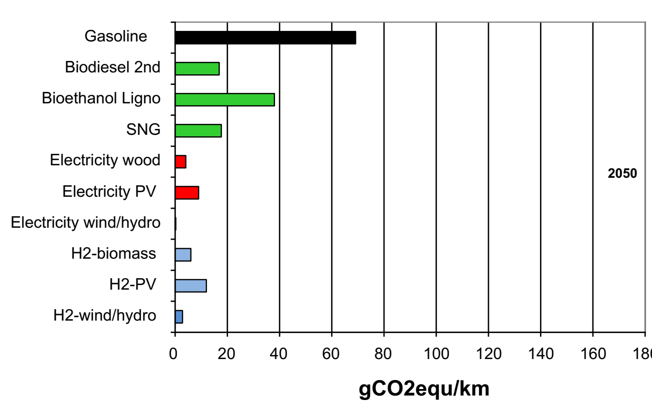

Fig. 3. Comparison of specific WTW CO_2 emissions in 2050 [14].

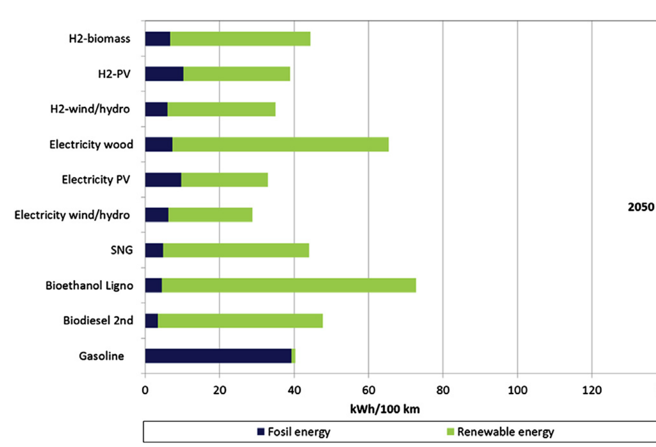

Fig. 5. Renewable and fossil energy distribution in the WTW energy service provision chain for gasoline versus renewable fuels [12], 2050.

In order to calculate the economic assessment of mobility with renewable fuels we have compared transport service costs per 100 km driven. In this context different driving distances play a role. The costs per km driven (C_{km}) are calculated as:

$$C_{km} = \frac{IC \cdot \alpha}{skm} + P_f \cdot FI + \frac{C_{O\&M}}{skm} \quad [€/100 \text{ km driven}] \tag{3}$$

where: IC, investment costs [€/car]; α, capital recovery factor; skm, specific km driven per car per year [km/(car.yr)]; P_f, fuel price incl. 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}) and excise tax (τ_{exc}). For the future we suggest to replace this excise tax with a CO_2-based tax.

$$P_f = C_f + \tau_{VAT} + \tau_{exc} \tag{4}$$

In the case of electricity the current electricity fee has been taken into consideration instead of an excise tax.

To capture the dynamic effects of changes in the investment costs in powertrains over time, we have applied the approach of technological learning on the investment cost of new technological components ($IC_{New\_t}(x)$) by using an exponential regression, learning index (b) and the investment cost of the first unit (a):

$$IC_{New\_t}(x) = a \cdot x_t^{-b} \tag{5}$$

The detailed method of the approach of dynamic economic assessment is documented in Ajanovic et al. [13].

Finally, we focus on how improvements in energetic performance influence the economic competitiveness of these fuels. Fig. 6 depicts the fuel costs of the service mobility in 2010 including taxes (excise tax and value added tax) for the average of EU-15 countries. Note that in these countries the excise tax range in 2010 was between 47% (Greece) and 63% (Germany) [19]. On average it was 59% of the retail gasoline price. Biofuels and hydrogen however are currently exempt from excise tax, and tax on electricity is much lower than excise tax on gasoline, see Fig.6. In 2010 the most expensive fuels per km driven were hydrogen and photovoltaic electricity.

The future use of renewable fuels depends largely on their economic performance as well as on the policy measures implemented which in turn may also affect which fuels are finally produced.

In this work it is assumed that the current excise tax will be replaced with CO_2-based taxes. The idea of the tax system we suggest is as follows: the highest excise tax in 2010, which was on gasoline, is converted in to a CO_2 tax of the same magnitude. For all other fuels this tax is set in relation to the WTW CO_2 emissions produced compared to gasoline. The implementation of this tax should begin in 2013 and increase by 0.015 EUR per kg CO_2 per year up to 2050. On this way renewable fuels with lower CO_2 emissions will have lower tax levels [11].

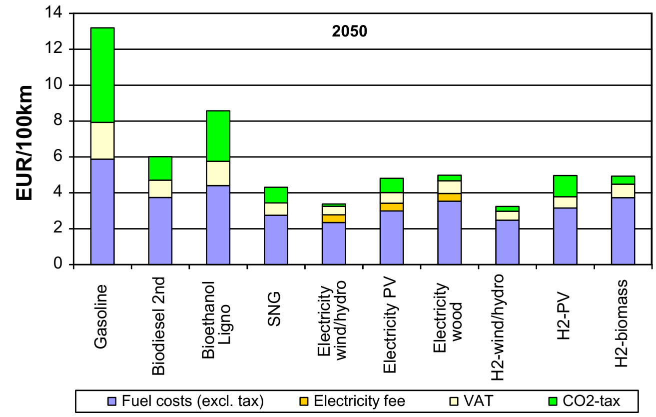

Fig. 7. Fuel costs of mobility in 2050 per 100 km.

As seen in Fig. 7, the fuels with the lowest WTW CO_2 emissions, wind and hydro power-based electricity and hydrogen, are also the cheapest by 2050. With a CO_2 tax all renewable fuels would become economically competitive with fossil fuels from about 2020. With no switch to a CO_2-based tax system, renewable fuels would become competitive with gasoline ten years later, in about 2030.

In the following diagram specific transport costs for different fuels and vehicles are shown per 100 km driven. (Biofuels are used in conventional ICE vehicles, electricity in battery electric vehicles, and hydrogen in fuel cell vehicles). As shown in Fig. 8 fuel costs play a relatively small role in the total transport costs, which are, especially in the case of electricity and hydrogen, largely determined by the capital costs of vehicles.

In order to model future cost developments we have used learning curves. The dynamic cost analysis in this paper has been based chiefly on IEA scenarios regarding international quantities [20]. In our model we split investment costs of vehicles into the costs of conventional mature technological components, and the costs of new technological components such as fuel-cells and batteries. With regards to conventional mature technological components no further learning is expected compared to a learning rate of 15% of new technological components.

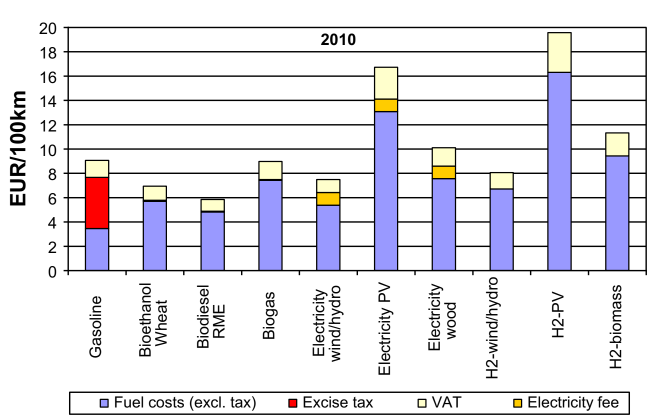

Fig. 6. Fuel costs of mobility in 2010 per 100 km based on average of EU-15 countries.

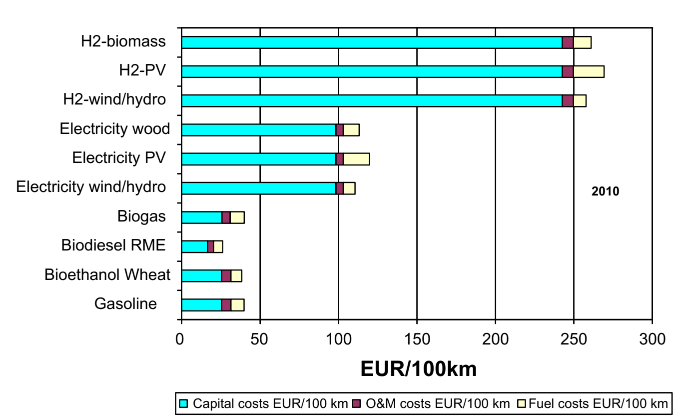

Fig. 8. Total specific costs of transport in 2010 per 100 km (car size: 80 kW).

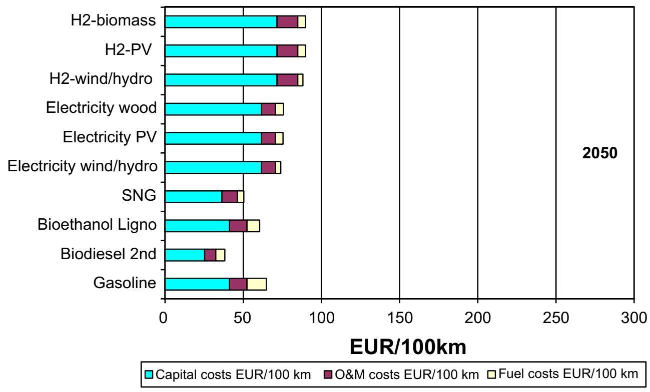

Fig. 9. Total specific costs of transport in 2050 per 100 km (car size: 80 kW).

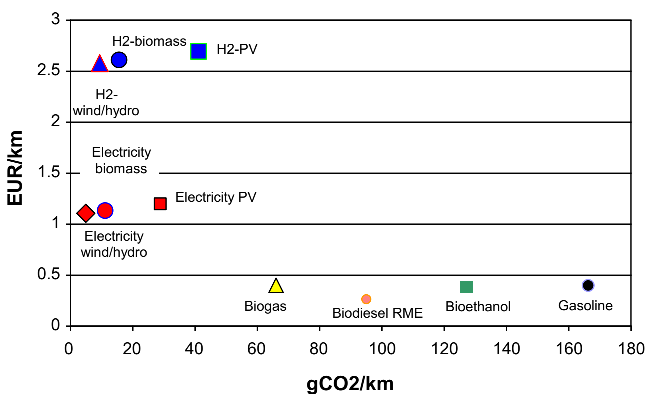

Fig. 10. Comparison of specific CO_2 emissions and costs of mobility for different fuels in 2010.

Through technological learning and larger production quantities, the investment cost of fuel-cell vehicles and battery electric vehicles could be significantly reduced by 2050 as well as fuel costs with a switch to a CO_2-based tax system. Fig. 9 shows the total specific costs of transport in 2050 per 100 km driven. Here we can observe that the total costs of service mobility in 2050 range far less than for same car size in 2010.

Which renewable fuels are used in the future will depend in the end on the total mobility costs and CO_2 balances. Fig. 10 provides a comparison of specific CO_2 emissions and costs of mobility with renewable fuels and gasoline.

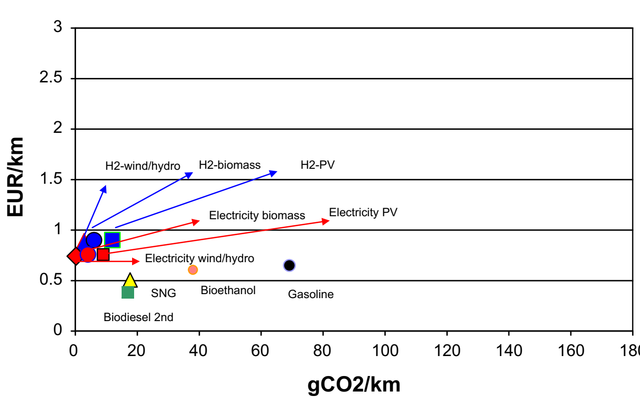

Fig. 11. Comparison of specific CO_2 emissions and costs of mobility for different fuels in 2050.

As outlined above, mobility provided today with renewable fuels, especially hydrogen and electricity, already has much lower WTW emissions than in case of conventional fuels and technologies. However the mobility costs with electricity and hydrogen are still much higher and are therefore not competitive on the market.

In the future this situation could change significantly through efficiency improvements, cost reductions (due to technological learning), the introduction of a CO_2-based tax system, and the switch from first to second generation biofuels. Fig. 11 compares specific CO_2 emissions and costs of mobility for different fuels in 2050 and we find with respect to costs as well as CO_2 emissions that the fuels analysed vary far less.

4. Conclusions

The key conclusions of this analysis are:

- The environmental performance of the first generation biofuels is currently rather modest. The economic prospects for first generation biofuels could be improved with the implementation of a CO_2-based tax system. Moreover, their potential is very restricted especially due to limited crop areas.
- Second generation biofuels are much more promising and could, in a favourable case, enter the market between 2020 and 2030. The major advantage of these biofuels is that they can be produced from different lignocellulosic materials, which are not in competition with food production. These advanced biofuels have a significantly better ecological and energetic life-cycle performance in comparison to first generation biofuels.
- While second generation biofuels could enter the market as early as 2020, first generation biofuels will remain on the market until 2030 at least. However if a CO_2-based tax is introduced it is very likely that first generation biofuels could become irrelevant in the long term if their ecological performance is not improved significantly.
- Despite very good CO_2 balances of hydrogen from renewable energy sources, the use of hydrogen in cars will not become competitive before 2050 due to high capital costs.
- We find that most probably by 2050 the total costs of the service mobility from the fuels analysed will vary far less than in 2010.

We conclude that renewable fuels will only play a significant role in the future if the appropriate balance between CO_2 taxes, intensified R&D, and technological learning is strategically implemented.

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