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基于能源排放统计的动力系统CO_2排放比较

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摘要：私人交通领域要实现可循环和可持续经济，就需要对二氧化碳排放有一个全面认知。从车辆能源供应角度看，要实现循环经济，需要去化石能源，发展可再生能源和绿色能源。在评估车辆动力系统的二氧化碳排放时，需要考虑从源头到末端的整个车辆能源供应系统的排放。本文选择了三种最常见的车辆能源动力系统，并选择了一个适用于对比的配置，来对比不同动力系统的二氧化碳排放情况。三种动力系统分别是电池电动汽车，燃料电池汽车及合成燃料混动汽车。本文首先介绍了三种动力系统的性能指标及其特性；其次对这三种动力系统的二氧化碳排放情况进行对比分析，包括整车和能源供应过程的排放，展示从源头到末端，车辆在其整个生命周期内的二氧化碳总排放量；最后通过对结果的分析与讨论，确定了最适用的车辆能源动力总成系统。

关键词： 车辆；能源供应；动力系统；碳排放
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Comparison of the Overall CO_2 Emissions of Different Powertrain Systems Depending on the Energy Sector Emissions

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Abstract: A circular and sustainable economy for the private transport sector requires a holistic view of the emitted CO_2 emissions. Looking at the energy supplied to the vehicle in terms of a circular economy leads to defossilisation. The remaining energy sources or forms are renewable electric energy, green hydrogen and renewable fuels. A holistic view of the CO_2 emissions of these energy sources and forms and the resulting powertrain technologies must take into account all cradle-to-grave emissions for both the vehicle and the energy supply. In order to compare the different forms of energy, the three most relevant forms of powertrain technology are considered and a configuration is chosen that allows for an appropriate comparison. For this purpose, data from the FVV project "Powertrain 2040" are used[1] and combined with research data on the energy supply chain for passenger cars. The three comparable powertrain configurations are a battery electric vehicle, a fuel cell electric vehicle and an internal combustion engine hybrid vehicle fueled with electric fuel. First, the three selected powertrain configurations are presented in terms of their performance, weight, technology and other characteristics. A comparative analysis is carried out for different CO_2 emissions of the electricity mix. The electricity mix is used for both the production of the vehicle and the energy. The results are presented in the form of cradle-to-wheel emissions, which consider the total CO_2 emissions of the vehicle over its life cycle. Finally, the results are analyzed and discussed to determine which powertrain technology fits best into which energy sector CO_2 emissions window.

Keywords: vehicles; energy supply; power system; carbon emission

1 Introduction

Current EU (European Union) legislation aims to reduce CO_2 emissions from private transport by 100% by 2035[2]. These targets conflict with the use of fossil fuels. The possible energy sources and forms are therefore severely restricted. At the same time, the variety of powertrain technologies is increasing enormously. These must not only react to new

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energy forms and carriers, but also increase in their energy efficiency, since an increase in prices for sustainable forms of energy is to be expected. It should be noted that zero exhaust emissions does not mean zero greenhouse gas emissions. If one considers the generation of energy or energy sources, it quickly becomes apparent that even supposedly renewable forms of energy offer an enormous greenhouse gas potential if they are produced with fossil energy sources. The greenhouse gas emissions merely occur at a different point in the production chain. Another crucial point is the generation of greenhouse gases during the production of the vehicles, which can be higher under certain boundary conditions with sustainable drive concepts than with conventional ones. For this reason, this paper takes a closer look at the production of energy sources and forms as well as the production of comparable vehicles with different powertrain technologies. Different scenarios for electricity production are considered in order to work out the optimal powertrain technology for given greenhouse gas emissions of the energy mix.

2 Energy and Fuels

If one considers the energy sources and forms which have the possibility of a complete defossilization of the production chain and a high availability, one end up with electricity, green hydrogen and e-fuels. However, this consideration requires a more precise definition. The electricity must be generated by renewable energy forms such as wind, solar, geothermal and possibly biomass. Also in this consideration, a greenhouse gas emission of zero is only possible if the complete life cycle of the renewable energy plants is defossilized. The minimum achievable greenhouse gas emission according to Ref. [1] is defined as 5 g CO_2 eq./(kWh). The sustainable production of hydrogen and e-fuels thus requires electricity from renewable energy sources, since fossil fuel production pathways either produce high greenhouse gas emissions or, in the case of carbon capture and storage, have limited storage capacity. The hydrogen must therefore be green hydrogen which is produced by an electrolysis process. Since the process is very energy-intensive, high greenhouse gas emissions can occur during production. For this reason electricity from renewable sources must be used. In the case of renewable fuels, the situation is even more complicated. A carbon source is needed for production. This can consist of biological feedstock, for example, and is referred to as bio-hybrid fuels. However, since the areas under cultivation are limited and this is therefore a niche product, it will not be discussed in detail. The second option is e-fuels, which are supplied with CO_2 via a carbon capturing plant. This removes CO_2 from the atmosphere and feeds it into the fuel production process. The carbon that is later emitted during combustion is thus completely removed from the atmosphere in the upstream production process. The result is a CO_2-circulation economy as can be seen in Fig. 1. In addition, green hydrogen is needed for production. In terms of overall efficiency for a total energy content to be generated, electric power thus emerges as the most efficient followed by hydrogen and e-fuels. Whereby it is to be mentioned that further factors for the use of an appropriate energy carrier and/or form can be like for example the transport and the storability.

Fig.1 CO_2-circulation economy for e-fuels using carbon capturing[3]

If one considers the greenhouse gas emissions of the renewable energy sources and fuels over the complete product life cycle, one obtains the well-to-wheel emissions. These are shown as a function of the greenhouse gas emissions of electrical energy generation and in relation to their energy content in Fig. 2.

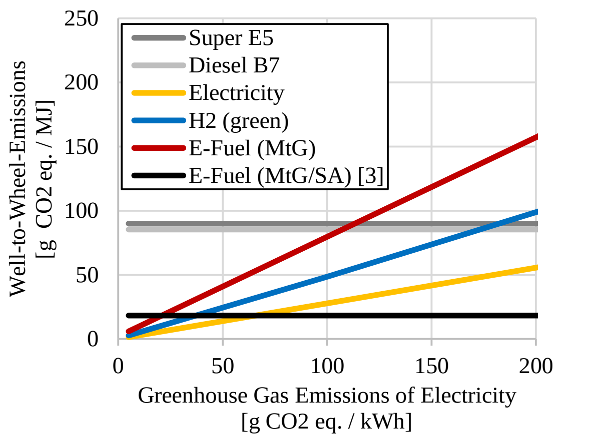

Fig.2 Well-to-Wheel-Emissions of conventional fuels, electricity, green hydrogen and e-Fuels (via MtG-Process)[3]

First, the well-to-wheel emissions of the conventional fuels used in the EU, Super E5 and Diesel B7, are shown. In addition, one scenario from Ref. [3] is added showing a scenario for e-fuel production in South America (SA). For all values above these fuels, the use of conventional and imported e-fuels is more efficient in terms of greenhouse gas emissions. For all values below the lines, the production in the EU becomes more efficient. It has to be mentioned that for the e-fuel produced in SA, the production emission will also decrease if the industry gets further defossilised. It only shows a snapshot of the current state of technology. It is noticeable that the electrical energy shows the best behaviour, followed by hydrogen and the e-fuels. This corresponds to the previously made assumption for the production efficiency of the considered energy sources and forms. For the further considerations and scenarios, different fixed values are always assumed for the greenhouse gas emissions of electrical energy. These therefore apply to both vehicle and energy source production. The production of regenerative energy sources and forms is assumed in the EU, except for the imported e-fuel from SA.

3 Vehicle Configurations

Three representative vehicle configurations of a C-segment sedan are selected for further consideration. These are taken from Ref. [1] and represent a technology status for the year 2040. In each case, the configurations are optimized for one of the energy carriers under consideration. In Fig. 3 the configurations are shown, with the battery electric vehicle (top), the fuel cell electric vehicle (middle) and the combustion engine hybrid (bottom).

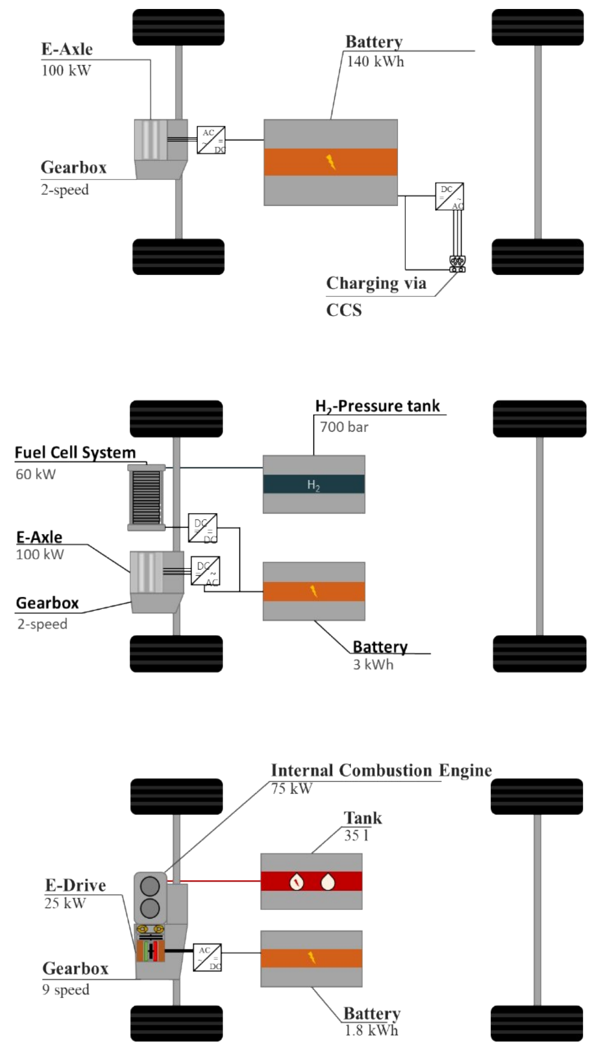

Fig.3 Representative powertrain configurations with battery electric vehicle (top), fuel cell electric vehicle (middle) and internal combustion engine hybrid (bottom)

An important factor for the energy consumption of the vehicle is its weight. In Fig. 4 the weights of the configurations are shown. It is noticeable that the combustion engine vehicle is the lightest, followed by the fuel cell vehicle and the battery electric vehicle. The differences are largely due to the battery weight. The well-to-wheel efficiencies for the different used driving cycles as well as the used drive cycle shares for the overall consideration can be seen in Tab. 1. The values for the energy consumption of the powertrains are optimized with the opt. MO-ECMS algorithm and are taken from Ref. [1] accordingly. The simulation is performed for four driving cycles which are composed to representative shares of a standard vehicle usage. The production of the vehicles is assumed in the EU.

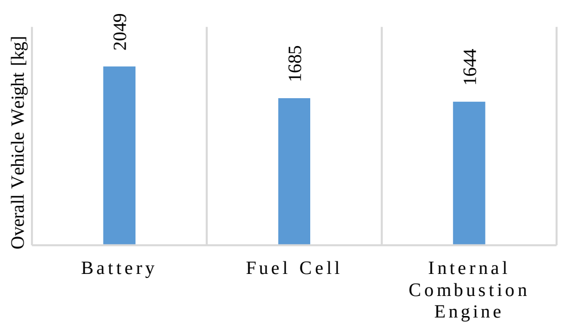

Fig.4 Overall Vehicle weight of the representative powertrain configurations[1]

Tab.1 Well-to-Wheel efficiencies and representative drive cycle shares for the three vehicle variants

Unit: %

Item	RDE	Commuter	Motorway	City
Cycle Share	50	20	20	10
$\eta_{overall,Battery}$	51	36	65	31
$\eta_{overall,Fuel\ Cell}$	22	15	29	12
$\eta_{overall,ICE}$	11	7	15	7

4 Results

The results of the greenhouse gas analysis for the three representative vehicles is presented in terms of cradle-to-wheel emissions. The disposal of the vehicle is neglected in this paper due to its low impact and assumed high recycling rates. The cradle-to-wheel emissions are made up of the cradle-to-gate emissions, i. e. the vehicle production, and the well-to-wheel emissions of the respective energy carrier or form. For the well-to-wheel-emissions, greenhouse gas emissions are accounted for over the entire product cycle. The vehicle service life is assumed to be 200 000 km. The vehicle production is assumed to be in the EU. Four scenarios are considered: 5, 50, 200 and 400 g CO_2 eq./(kWh) for the production of electrical energy. Where according to Ref. [1] 5 g CO_2 eq./(kWh) represents a minimum for the greenhouse gas potential for the electric energy production. The German electricity production is currently in the range of 400 g CO_2 eq./(kWh) and for the EU around 200 g CO_2 eq./(kWh). With 50 g CO_2 eq./(kWh) a strongly defossilized energy sector is shown, which is not yet fully optimized. In Fig. 5, cradle-to-wheel emissions are shown for the battery electric and fuel cell electric vehicle, as well as for the internal combustion engine vehicle, for fossil and e-gasoline (MtG). The figure contains two different scales and the emissions are plotted over the greenhouse gas potential of electricity generation.

The top figure shows that the ICE hybrid with e-fuels produced in South America has the lowest cradle-to-wheel emissions up to an electricity global

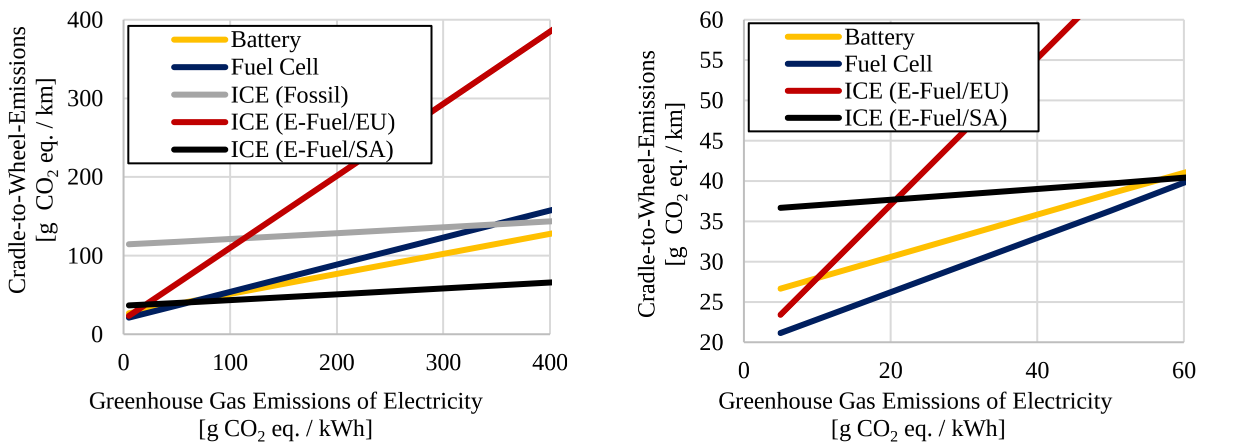

Fig.5 Cradle-to-Wheel-Emissions of conventional gasoline, electricity, green hydrogen and e-Fuels (via MtG-Process), with up to 400 g CO2 eq./(kWh) electricity generated (top) and up to 60 g CO_2 eq./(kWh) (bottom)

warming potential of 62 g CO_2 eq./(kWh). The battery electric vehicle already has a lower greenhouse gas potential at 400 g CO_2 eq./(kWh) than an internal combustion engine hybrid that is fuelled with conventional fuel. The fuel cell electric vehicle becomes more efficient than the vehicle with conventional fuel from approximately 350 g CO_2 eq./(kWh) and when using e-fuels produced in the EU the limit is around 113 g CO_2 eq./(kWh). The figure at the bottom shows a further effect. Due to the higher production emissions of the battery electric vehicle, the fuel cell electric and the ICE vehicle have advantages when the well-to-wheel emissions of the energy sources and forms decreases.

Fig. 6 shows the breakdown between vehicle production and well-to-wheel emissions for the three representative vehicle variants and the four EU energy scenarios. It can be seen that the greenhouse gas emissions for the production of the battery electric vehicle are the highest, followed by the fuel cell electric and ICE vehicle. Furthermore, it is noticeable that the greenhouse gas emissions for the energy sources and forms of energy scale more sharply than the production emissions. Again, it can be observed that the well-to-wheel emissions are lowest for the battery electric and highest for the ICE vehicle. In addition to the production efficiency, the efficiency of the powertrain, as it can be seen in **Table 1**, results in an even stronger scaling of the well-to-wheel emissions.

5 Conclusion

The present paper shows that for all three relevant renewable energy forms, electric, green hydrogen and e-fuels, a reduction of the greenhouse gas potential compared to fossil fuels can already be achieved at relatively high specific greenhouse gas emissions for electricity generation. For low specific greenhouse gas emissions in electricity generation, all three energy forms converge and there is almost no difference between the powertrain types. Particularly for e-fuels, due to their good transportability, production sites in island operation are conceivable. These can already be operated completely with regenerative energy plants today and thus contribute to an enormous reduction of greenhouse gas emissions by the existing fleet [3]. It should be mentioned that the transportability, infrastructure and cost of renewable energy an energy carriers also play an important role for the market introduction of the presented technologies.

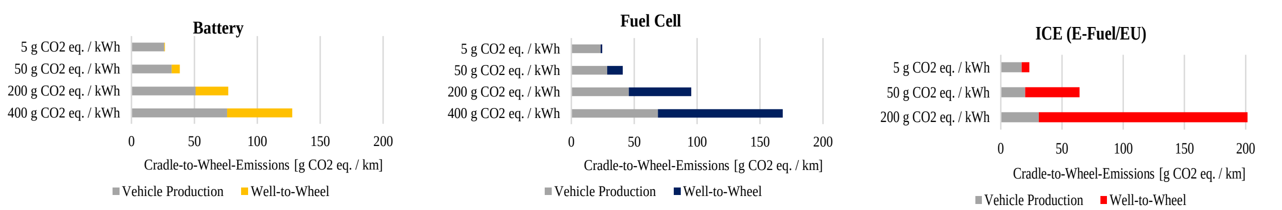

Fig.6 Vehicle Production (Cradle-to-Gate) and Well-to-Wheel-Emissions for battery electric (top), Fuel Cell (mid) and ICE wit e-fuel vehicle (bottom)

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