Comparing drive train concepts beyond GHG emissions – an efficiency approach

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Background

For decades light vehicles have been almost solely powered by combustion engines using fossil diesel or gasoline. Road transport therefore is an important source of greenhouse gas emissions today and a considerable reduction in CO_2 emissions is necessary. To this end, numerous regulations, labels and goals were put into place, both on national and EU level, the most important of which are listed in Table 1.

Table 1: Measures concerning fuel economy and CO2 emissions

measure	domain	description
fleet emission performance standards (EU 2009a)	EU	car manufacturers are bound to reduce average tailpipe emissions of their vehicle sales to an EU average of 130 g/km (dependent on vehicle weight) by 2015
renewable energy directive (EU 2009b)	EU	goal of 10 % renewable energy in the transport sector by 2020
CO_2 efficiency label (German Fed. Governm. 2011)	Germany	CO_2 efficiency classes to new vehicles (currently ranging from A+ to G) based on tailpipe CO2 emissions (weight dependent)
CO_2 dependent vehicle taxation	Germany	about 50 % of vehicle tax based on CO_2 tailpipe emissions
energy concept (German Fed. Governm. 2010)	Germany	10-percent reduction of final energy consumption by 2020 (compared to 2005) in the transport sector and a 40-percent reduction by 2050 (not legally binding)

It can be seen that the legally binding goals and regulations solely focus on tailpipe CO_2 emissions, which leads to three major problems:

1. Vehicle oriented measures and regulations which refer to tailpipe emissions cannot indicate changes in the upstream energy pathway e.g. by increasing exploitation of unconventional oil deposits or the customer's choice to fuel his car with bioethanol.

2. Alternative drive train concepts like battery or fuel cell electric vehicles, as well as different concepts of hybridization, are entering the mass market. This will cause a systematic shift of CO_2 emissions from the tailpipe to power plants and refineries. This leads to a disability of tailpipe regulation to effectively cut down overall CO_2 emissions.

3. The tailpipe emissions of hybrid vehicles, which are expected to represent the majority of alternative drive train concepts in the medium term, depend strongly on the driving pattern. Emission test procedures of these vehicles thus only represent one possible use pattern.

As a result, current regulation favours drive train concepts with little or no tailpipe emissions (mostly with electricity as intermediate energy source). These are even further privileged since low emission vehicles are counted multiply in fleet emission performance standards until 2015 in order to foster their market introduction. Additionally, electricity is subject to lower taxes than fuel in many European countries. Thus there are no real incentives for manufacturers to optimize energy efficiency of these concepts

Considering these facts, it seems necessary to take a closer look at energy demand and energy efficiency and how today's and tomorrow's drive train concepts perform in this respect. This paper aims to do this by both looking at generic energy pathways and applying the results to particular use cases. Finally, conclusions will be drawn regarding possibilities to complement the existing CO_2 focused regulation with an efficiency focus. Since energy efficiency is closely related to cost efficiency, the customer's perspective will be explicitly considered.

Efficiency of different drive train concepts

Efficiency is defined as the ratio between a benefit (output) and the necessary effort (input). In the case of light vehicles, the latter is essentially the transport of persons over a given route (distance).The vehicle kilometer over a certain driving cycle[1] will be the reference for the following discussion since the load factor (persons travelling divided by offered seats) of a vehicle is not mainly determined by technical, but rather economic and social factors. Furthermore, we will not discuss to which extent certain driving cycles represent real world conditions.

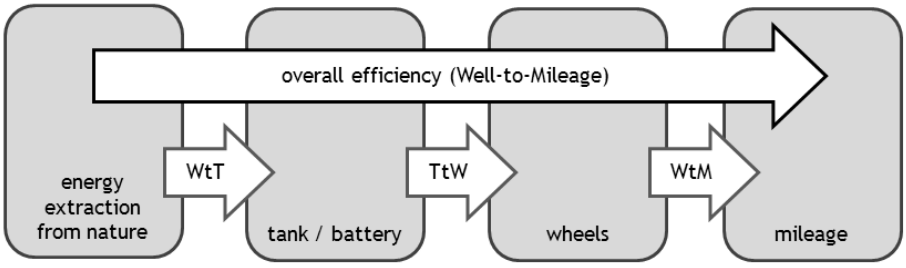


Figure 1: Schematic diagram of considered efficiencies

For our discussion we divide the vehicle efficiency chain into sections as shown in Figure 1. Commonly, only Well-to-Tank (WtT) and Tank-to-Wheel (TtW) efficiency are looked at. Since the selection of the drive train may also influence vehicle parameters like weight or aerodynamic drag, we additionally introduce a "Wheel-to-Mileage" efficiency (WtM) which indicates the distance a vehicle is able to run with a certain amount of energy at the wheel. In the following, we will discuss some relevant drive train concepts and energy pathways along these categories.

Energy calculations for different scenarios are done using the vehicle LCA model "eLCAr" which was developed and is continually updated and extended by IFEU (Helms et al. 2011). It comprises all stages of a vehicle life, i.e. vehicle production, use, maintenance and disposal as well as energy supply for all stages.

Well-to-Tank efficiency

In order to determine well-to-tank-efficiency, the cumulated energy demand for the production of fuel resp. electricity with an energy content of 1 MJ is calculated. It is differentiated by renewable (e.g. biomass, wind) and non-renewable (i.e. fossil and nuclear) energy sources (Figure 2).

Electricity pathways are calculated using IFEUs in-house electricity model (see Helms et al. 2011), wherein the energy demand for wind power is defined as the energy fed into the generator and an old lignite power plant is assumed to have an efficiency of 30,5 %. The data for hydrogen pathways is taken from (Henes 2011), fuels from tar sands are modelled according to (Schimpf 2010). Biofuels are based on (Fehrenbach and Kunze, 2011), wherein the selected pathways represent the situation for Germany. Details on fossil fuel data are described in (Helms et al., 2011). The overall selection focuses on pathways which are either currently

[1] Figures in this paper are based on the real world cycles of the 'Handbook of Emission Factors' (HBEFA) (INFRAS 2010) which are weighted by the rounded shares of average driving with medium size passenger cars in Germany according to TREMOD (Knörr 2009), leading to 30 % urban, 40 % extra-urban and 30 % highway driving.

dominating (i.e. fossil fuels) or are expected to become important in the medium-term future (e.g. Ogden and Anderson 2011).

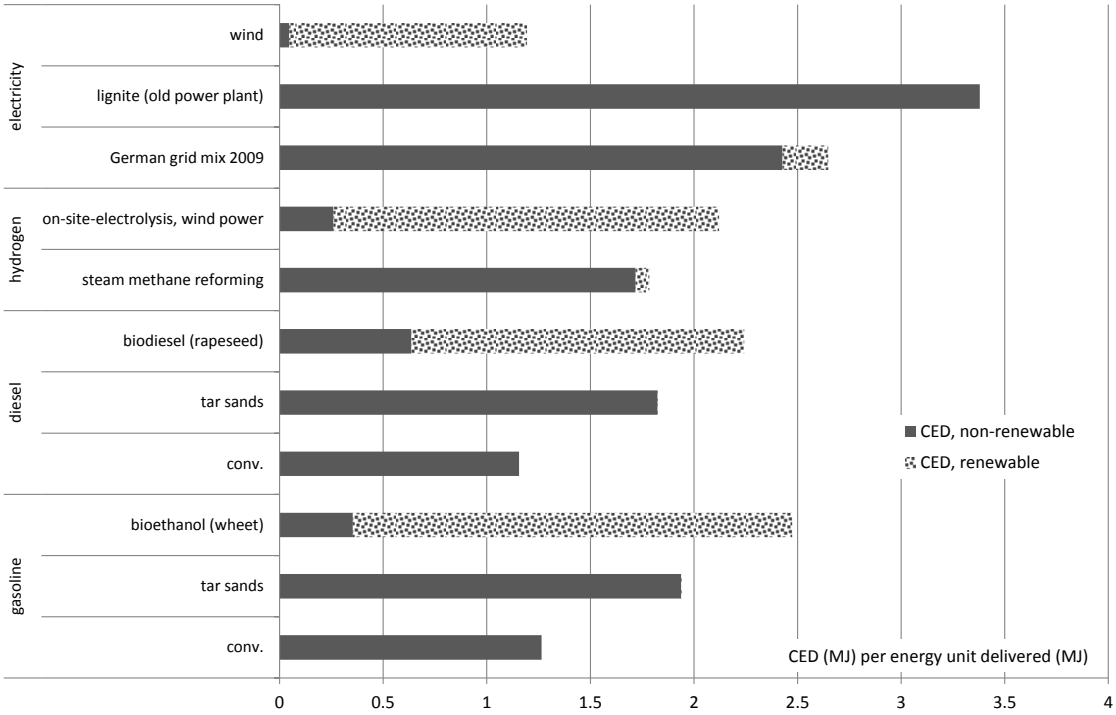


Figure 2: Cumulated energy demand per energy delivered to the tank/battery for different energy sources

It is important to note that the future trends for fuels and electricity are reverse: While the rising share of renewables (mainly wind and solar power) in electricity production tends to increase WtT efficiency according to our definition, the use of renewable energy for biofuel production increases primary energy demand per gallon significantly. This effect could only be decreased if biofuels of the second or third generation became ready for the market. Moreover, due to depletion of oil fields and increasing worldwide demand, it is likely that unconventional oil deposits such as tar sands will become more common, which feature an energy intensive extraction process.

Tank-to-Wheel efficiency

Variations in TtW-efficiency between the power trains are of the same order of magnitude as the WtT efficiency (Figure 3). The battery electric vehicle (BEV) is by far the most efficient one, reaching between 80 % and 90 % conversion efficiency in the electric motor. However, the energy storage, namely the battery, cannot be neglected, leading to a further energy loss of about 10 %. An important parameter in this context is the ambient temperature: if it is low (especially below 0° C), the battery efficiency can drop dramatically (DEKRA 2011).

The efficiency of fuel cell electric vehicles (FCEV) is mainly determined by the electrochemical processes in the fuel cell; current vehicles reach about 50 % conversion efficiency. Since the power output of the fuel cell is limited, a battery is needed to cover peaks in the vehicle's power demand.

ICEV have the lowest TtW efficiency, limited essentially by thermodynamic limits. In spite of this, there are various approaches for efficiency enhancements of ICEV, particularly through optimized fuel injection technologies.

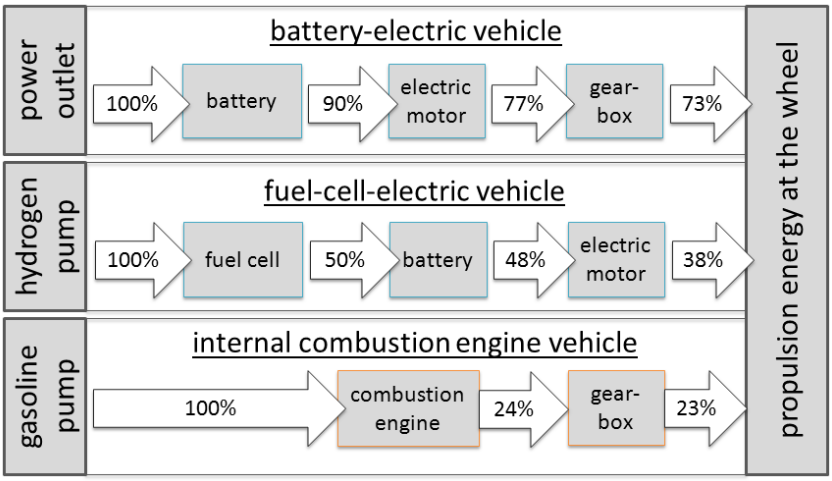
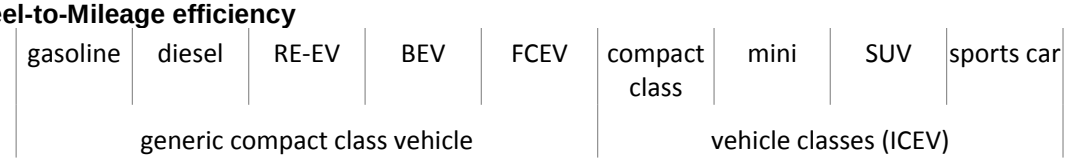


Figure 3: Tank-to-Wheel efficiency for different power trains

Wheel-to-Mileage efficiency



the power train and the vehicle class are varied separately; again, an average German driving pattern is used as defined above. In the first case, only the mass difference due to the power trains is considered, which leads to a higher energy demand of the heavier electric vehicles.

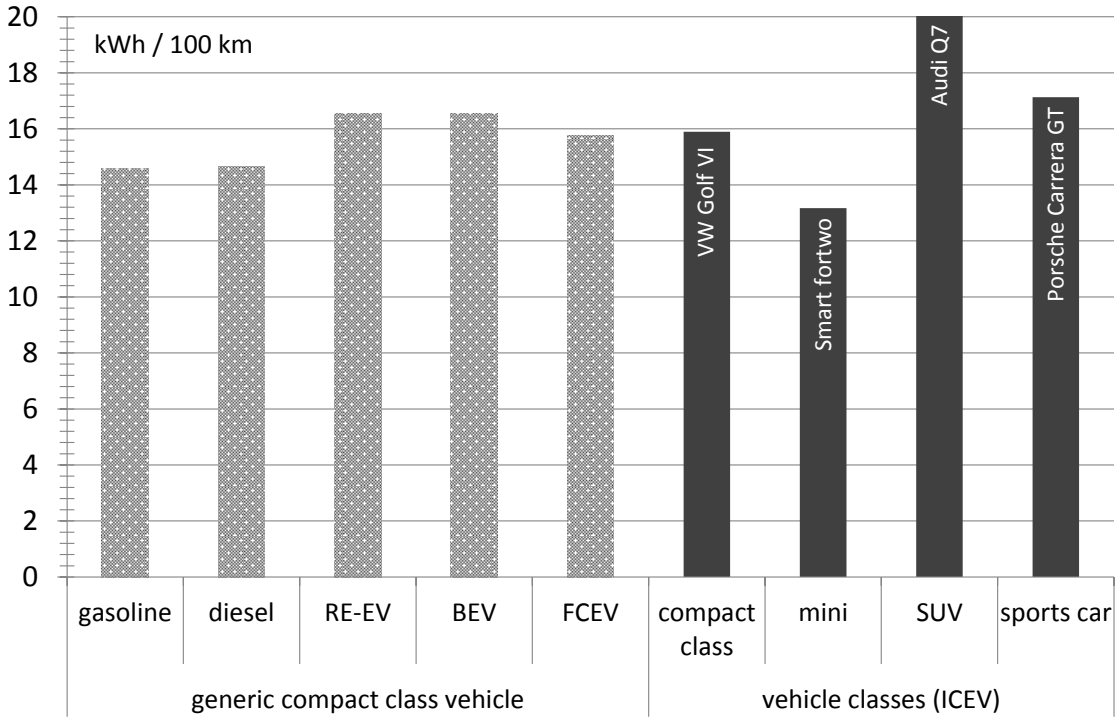


Figure 4: Physical energy requirement at the wheel for a) a generic compact class vehicle, equipped with different power trains (based on data from Helms et al. 2011) and b) different vehicle classes (based on vehicle data of the respective manufacturers)

It can be seen that although differences due to the power train are significant, the vehicle class has even more influence on WtM efficiency: Especially heavy and bulky vehicles like SUVs have a higher energy demand.

Overall efficiency (Well-to-Mileage)

In the following, the total efficiency is presented for some relevant combinations of drive train and energy supply, which covers WtT, TtW and WtM efficiencies discussed before. First, this is done for a reference compact car to compare the considered power trains, afterwards variations between four different vehicle examples are discussed.

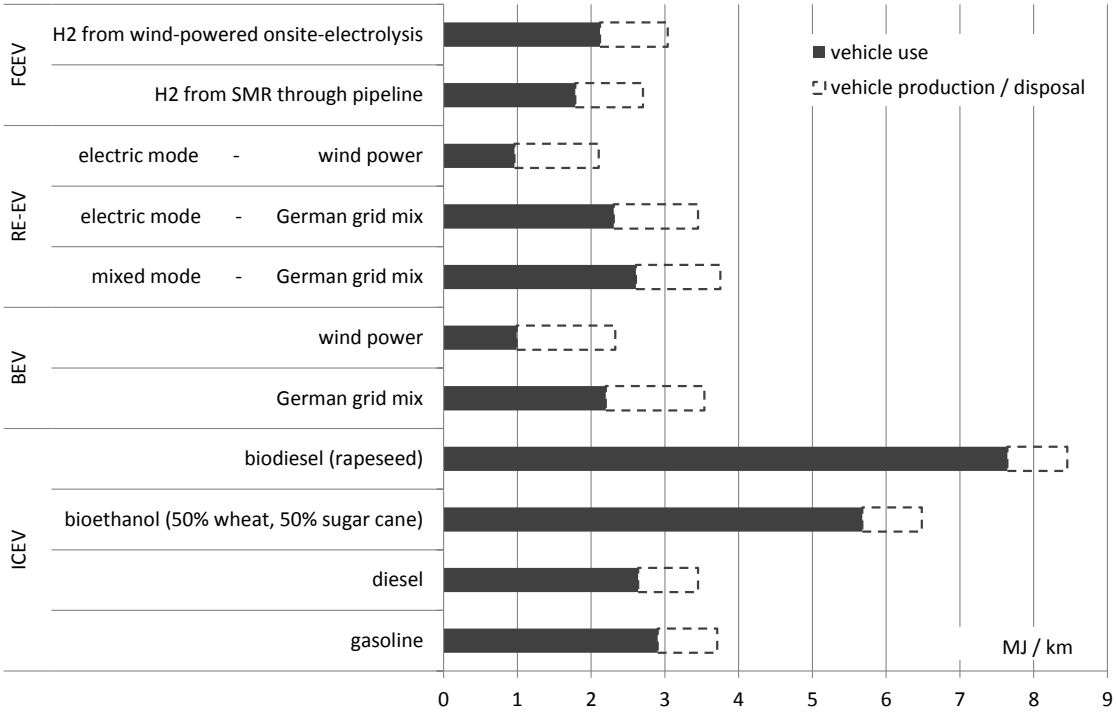


Figure 5: Energy demand (well-to-milage) of a middle-class vehicle with different drive trains and energy pathways

With regard to Figure 5, the following can be stated:

1. ICEV powered by biofuels of the first generation (which are at the moment mostly blended with fossil fuels) have an exceptionally high energy demand compared to all other considered pathways. Although if the cumulated energy demand is covered to a large extent by renewables (i.e. biofuels), their potential is not used most efficient. Renewable in ICEVs should thus only be used were other alternatives, like electric power trains, are not able to substitute combustion engines (e.g. in long distance freight transport).

2. Direct use of renewable electric energy in Plug-in electric vehicles (Plug-in hybrid EVs, RE-EV and BEV) is overall by far the most energy efficient pathway

3. The additional energy conversion steps in hydrogen production (like hydrogen electrolysis) leads to a less favorable use of renewable electricity.

4. With alternative drive trains, the share of energy required for vehicle production becomes more important in comparison with the use phase. This is mainly due to the energy intensive production of battery and fuel cell, respectively. However, since establishment of data for vehicle production requires detailed knowledge of the production process, it will be difficult to consider it in the quantification of individual vehicles.

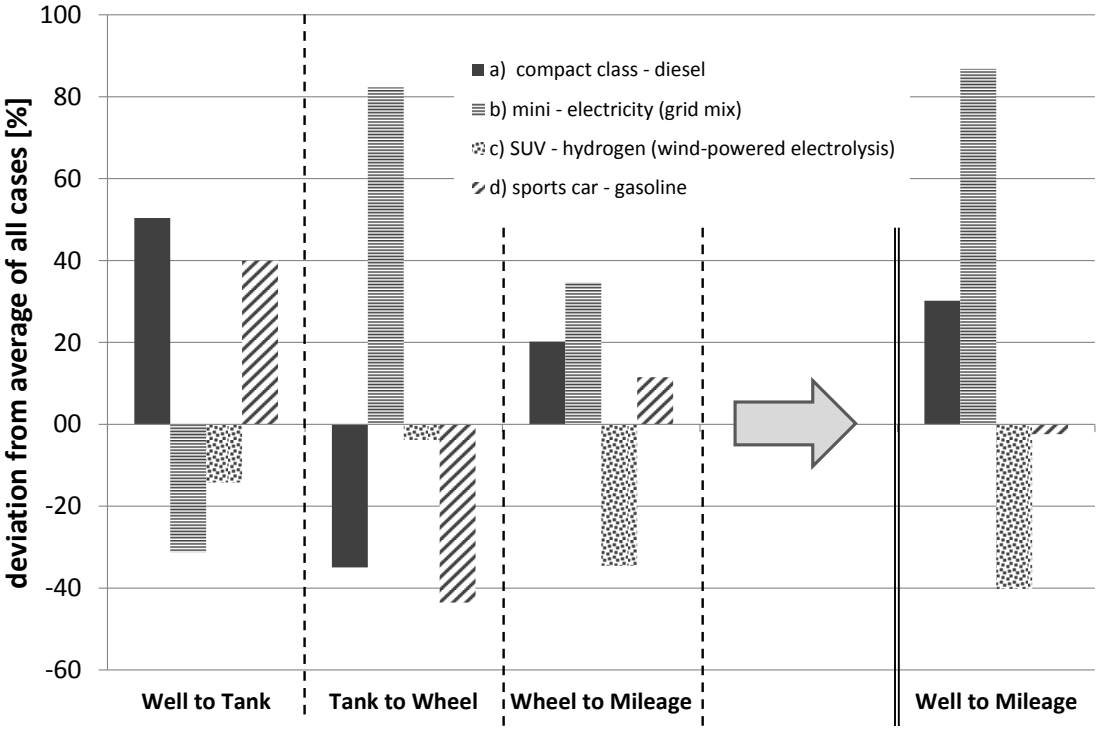


Figure 6: Normalized efficiencies for some exemplary cases (0 = average of all vehicle configurations).

As a final step, we apply the demonstrated approach for efficiency assessment to four different exemplary vehicle configurations[2] in order to calculate the Well-to-Mileage efficiency:

a) A diesel compact car (like the VW Golf), which represents a large share of today's sales, is assumed to use fossil diesel fuel in Germany with a 5 % biodiesel blend. The good well Well-to-Tank efficiency is somewhat balanced by the low Tank-to-Wheel efficiency of the combustion engine. Overall efficiency per mileage, however, is still favorable, also due to the comparably low vehicle weight.

b) A small electric city vehicle (like the Smart fortwo) uses average electricity from the German grid. Well-to-Tank efficiency of the German grid is comparably low due to large share of coal power, but the Tank-to-Wheel efficiency in the vehicle more than compensates for this drawback. The low weight and air drag of the small vehicle even further improve the efficiency so that this configuration turns out to have the highest overall efficiency.

c) A fuel cell sport utility vehicle (SUV) is assumed to use hydrogen produced by local on-site electrolysis using wind power. The Well-to-Tank efficiency is somewhat unfavorable due to the conversion step of the electrolysis. Though Tank-to-Wheel efficiency is about average, the high energy demand at the wheel due to vehicle weight and size leads to the worst overall energy efficiency per mileage.

d) A sports car (like the Porsche Carrera) is assumed to use fossil gasoline in Germany with a 3 % bioethanol blend. As for the diesel vehicle, Well-to-Tank efficiency is high but somewhat balanced by the low Tank-to-Wheel efficiency of the combustion engine. Overall efficiency turns out to be just below average.

[2] Resistance parameters such as weigh, front size and air drag have been considered as vehicle specific parameters, while for engine efficiency, typical values have been used, which do not take into account the specific vehicle type or model.

Conclusions

It has already been stated in the introduction, that the perspective of energy consumption is also the perspective of the consumer, because energy is what the consumer pays for – not (yet) CO_2-emissions. In this respect the communication of electric vehicles as zero emission vehicles is not giving much advice whether this is an efficient vehicle and about how high variable costs will be.

Since the existing legislation and most political targets are based on CO_2-emisisons, an efficiency approach at vehicle level is not likely to substitute this perspective in the near future. Complementary consumer information on vehicle efficiency at various levels as presented, however, would be an option, which also allows for an identification of weaknesses and strengths of certain vehicle types and manufacturers. This approach provides information beyond the obvious fact that an SUV consumes more energy than a compact car. It will also become apparent if a large and heavy vehicle despite its high overall energy consumption has a very efficient drive train or if a small vehicle despite its comparably low energy consumption due to the low weight and dimensions, could be further optimized in terms of drive train efficiency.

More problematic for consumer information appears to be the evaluation of WtT-emissions since they are subject to changes over time which can only partly influenced by the consumer (e.g. by using green electricity or biofuels). In any case such choices are not permanently linked to the vehicle and its performance. Furthermore, while vehicle efficiency can also be determined based on certain parameters already available or deducted during the type approval process, the harmonized assessment of energy supply at a comparable level is more challenging and not yet an established part of vehicle market introduction.

Finally, also from an environmental point of view energy efficiency is of importance: Though renewable electricity also leads almost emission free vehicle operation even if WtT emissions are considered, renewable energy remains a limited good. This good should therefore not be wasted lightly since it could substitute further fossil energy carriers elsewhere.

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