How to decarbonise heavy road transport?

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Abstract

Ambitious long-term greenhouse gas (GHG) emission targets require decarbonisation of the transport sector. Where plentiful supplies of low carbon electricity are available for road transport, passenger cars with internal combustion engines need to be replaced by electric vehicles. However, despite its growing share of transport's CO_2 emissions, no clear solution presents itself for CO_2 emission reduction on heavy road transport. Potential low carbon options include direct electrification of trucks via batteries, over-head power lines, hydrogen and other power-to-X fuels from renewable electricity. Here, we compare these options with respect to their degree of technological readiness, economy, infrastructure costs and CO_2 reduction potential. We use cost assumptions and cost reduction potential from available literature sources and combine them with actual heavy truck usage data for an analysis for Germany in 2030. Our results show that the high efficiency in direct usage of electricity from catenaries implies less installation of additional renewable power compared to fuel cell electric vehicles. Both could be good long-term solutions but require a massive initial infrastructure investment.

Introduction

Global warming and the dependence on limited fossil fuels force the world to think about alternative solutions. In the transport sector, plug-in electric vehicles, fuel cell electric vehicles or natural gas vehicles are often discussed as one means to reduce carbon dioxide (CO_2) emissions. However, this only refers to passenger cars and light duty vehicles. The on-road freight transport sector with larger vehicles is often neglected although it is responsible, for about one third of CO_2 emissions road transport sector with only one tenth of the vehicles in Germany [BMU 2013]. Also, the transport volume is still rising in this sector. If the German goal to reduce CO_2 emissions in the transport sector by 40 % in 2030 compared to 1990 [BR 2016], the heavy road transport sector has to at least stop to increase its emissions. However, a long-term goal of a CO_2 emission-free transport sector could cause a short- to medium-term increase in CO_2 emissions as well, when electricity is used that is not solely from renewable energies.

Table 1 shows the distribution of vehicles in the on-road freight transport sector in Germany by gross weight at the moment. Light duty vehicles with a weight of less than 3.5 tons are driven about 13,000 km per year, yet they have the largest vehicle stock compared to heavier trucks. With increasing weight, the annual vehicle kilometers travelled (VKT) are rising up to an average of 114,000 km for heavy duty trucks. While their vehicle stock is much smaller than for light duty trucks (about one tenth), the annual vehicle mileage in both size classes is about the same because of the higher VKT. By further comparing the specific CO_2 emissions in the different size classes, we find the much greater impact of heavy duty vehicles on the environment – heavy duty vehicles are the most emitting and energy consuming vehicle class compared to the smaller ones. Although the smaller trucks also need attention, we focus on heavy duty vehicles with an allowed total weight of 40 tons.

This paper aims at showing possible emission-free technology solutions for the heavy road transport sector from a technical,

Table 1. Overview of heavy road transport.

Vehicle size	Unit	Light commercial vehicle	Light duty vehicle	Medium duty vehicle	Upper medium duty vehicle	Heavy duty truck
Allowed total weight	Tons	(0 t; 3,5 t]	(3,5 t; 7,5 t]	(7,5 t; 12 t]	(12 t; 26 t]	(40 t)
Average annual vehicle kilometres travelled	km/a	ca. 13,000	ca. 27,000	ca. 66,000	ca. 74,000	ca. 114,000
Vehicle stock	vehicles	ca. 2,000,000	ca. 262,000	ca. 77,000	ca. 161,000	ca. 183.000.
Annual vehicle kilometres travelled	fkm/a	26 billion	7.1 billion	5.1 billion	11.9 billion	19.4 billion
Specific CO_2 emission WtW (1) (2)	g CO_2/km	241	431	594	781 (3)	1,016
CO_2 emission WtW	million t CO_2/a	6.3	3.0	3.0	9.3	19.7
Total energy consumption TtW (4)	TWh/a	19.0	9.2	9.1	28.1	59.5

(1) Well-to-Wheel emissions; (2) average of all street categories, Euro-VI, load factor: 50 % (3) weighed with the average vehicle stock of trucks >14–20 t and trucks >20–26 t; (4) Tank-to-Wheel emissions. References: (KBA 2014, KBA 2015, HBEFA 3.1, Truckscout 2013).

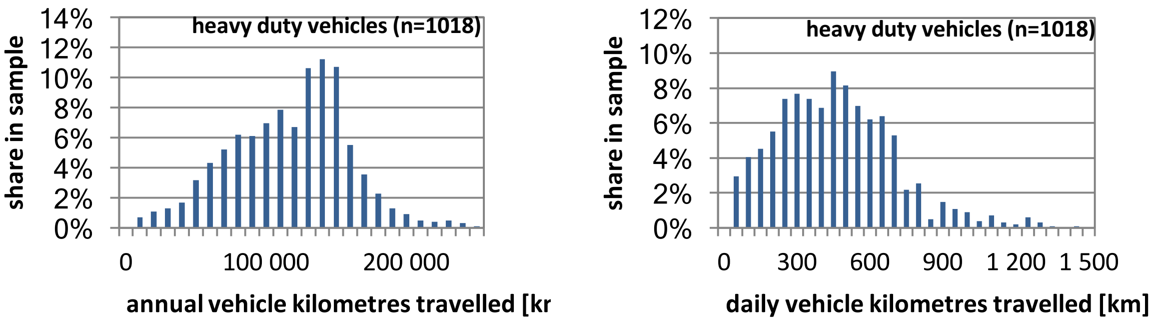

Figure 1. Annual and daily vehicle kilometres travelled by heavy duty vehicles. Data from [KiD2010].

economical and environmental perspective. We compare technologies for 2030, but also have long-term goals in mind. It is structured as follows. In the following section, the methodology, data and assumptions are presented. Thereafter, results are shown in the three afore-mentioned categories and in a synopsis for all solutions. A discussion and conclusions round up this paper.

Data, Methods and assumptions

DATA

For the analysis of heavy duty vehicles in Germany, we use the data set "Kraftfahrzeugverkehr in Deutschland 2010" (KiD2010) which is a travel survey of about 70,000 vehicles with all vehicle movements on one day of observation [KiD 2010]. This data set is publicly available and the largest sample of commercial vehicle movements in Germany. Based on the size class information, we can filter out the vehicles with an allowed total weight of 40 tons and receive 1,018 vehicles for our analysis. We only use two attributes of the sample: the annual VKT and the VKT on the day of observation both reported in an accompanying questionnaire to the data collection. The distributions of both variables are shown in Figure 1.

We can see that the annual vehicle kilometres travelled peak at 130,000–150,000 km while there is not such a clear peak for the daily VKT. This implies that vehicles are not used every day or that the frequency of usage is different for the vehicles. In the results section, we will focus on the annual VKT and show cost calculations for the quartiles (q_{25}=81,492 km, q_{75}=141,777 km).

METHODS

We compare alternative drive trains for heavy duty vehicles in three ways: a technical, an economical and an environmental analysis. For all three analyses the methods are described as follows.

Technically the drive trains differ in their well-to-wheel (WtW) efficiency. Thus at first, we compare the WtW efficiency for several fuel types. The differences are caused by multiple conversions of electricity to the designated fuel and then to movement energy in the vehicle. This permits a provision of completely renewably powered fuels. However, we will use the electricity mix in 2030 to compare their emissions (from an environmental perspective).

Secondly, the drive trains are at different stages of development at the moment. We will thus use the technological readiness level to compare them against each other [EC2015]. According to the classification of the European Commission nine stages are specified as follows:

- TRL 1. basic principles observed

- TRL 2. technology concept formulated
- TRL 3. experimental proof of concept
- TRL 4. technology validated in lab
- TRL 5. technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 6. technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies)
- TRL 7. system prototype demonstration in operational environment
- TRL 8. system complete and qualified
- TRL 9. actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies; or in space)

The third part of the technical comparison comprises a discussion of driving ranges.

The decision about a drive train in heavy duty vehicles is mainly based on cost [Globisch and Dütschke, 2013, Sierzchula, 2014]. Most commercial car holders and logistics companies base their decision on per-kilometre cost [Plötz et al. 2014b, Wietschel et al. 2017]. For this reason, we compare the total cost of ownership as cost per kilometre for several fuel options.[1] The total cost of ownership (TCO) contains a cost for the capital expenditure which is divided by the annual VKT to be comparable to the kilometre-specific cost for the operating expenditure.

The cost for the capital expenditure is calculated as follows:

$$a_{capex}^{f} = \frac{I_s \cdot (1+i)^{\mathrm{T}}\, i}{(1+i)^{\mathrm{T}} - 1} \cdot \frac{1}{\mathrm{VKT}_f} \qquad (1)$$

I_s	Investment for vehicle of drive train s [EUR]
i	interest rate
T	Investment horizon [a]
VKT_f	annual vehicle kilometres travelled in vehicle f

The investment for the vehicle $I_{s,t}$ is discounted to an annuity $a_{capex}^{f,t}$ with interest rate i and investment horizon T. Thereafter, it is divided by the annual vehicle kilometers travelled VKT_f in driving profile f.

The cost for operating expenditure is calculated as:

$$a_{opex}^{f} = \left(s_{e_f} \cdot c_{e_s} \cdot k_{\mathrm{e}} + \left(1 - s_{e_f}\right) \cdot c_{\mathrm{s}} \cdot k_{\mathrm{c}}\right) + k_{\mathrm{O\&M}_s} \qquad (2)$$

s_{e_f}	share of driving in with primary fuel in driving profile f (:=1 if not a hybrid vehicle)
c_{e_s}	primary consumption of vehicle with drive train s [kWh/km]
k_e	cost for primary fuel [EUR/kWh]
c_{c_s}	secondary consumption of vehicle with drive train s (only for hybrid vehicles) [kWh/km]
k_{c_t}	cost for secondary fuel (only for hybrid vehicles) [EUR/kWh]
$k_{O\&M_s}$	cost for operations and maintenance for drive train s [Euro/km]

Thus, for the operating expenditure, we focus on cost for fuel and maintenance ($k_{O\&M_s}$) and consider variations for hybrid vehicles with two different fuels. Aspects like heavy duty vehicle toll, insurance, vehicle registration tax and cost for the driver are equal between different drive train technologies today and, for the purpose of this study, no changes until 2030 are included.

From an environmental perspective, we take a look at the CO_2 emissions. Additionally, we calculate the total renewable energy consumption during the use phase needed for a complete replacement of all heavy duty vehicles. This permits to understand the feasibility of a complete replacement under environmental constraints.

TECHNO-ECONOMICAL ASSUMPTIONS

In this analysis, we compare five different drive trains: Diesel vehicles as the benchmark technology, vehicles driven by liquefied natural gas (LNG), fuel-cell electric vehicles (FCEV), battery electric vehicles (BEV) and catenary hybrid vehicles (CHV). While the first five options contain only one drive train, CHV are considered to be able to drive with electricity on the catenary and with diesel otherwise.[2] To compare these drive trains for heavy duty trucks, we need a variety of assumptions concerning the vehicles that are listed in Table 2 for Germany in 2030.

We list the investment, their consumption, their cost for operations and maintenance (O&M), their range if it differs largely from diesel vehicles and their CO_2 emissions. All values are given for 2030 and taken from literature, all prices are given without value added tax in EUR_{2016}.

A diesel vehicle in 2030 is assumed to cost about EUR 130,000 and all other drive trains have to pay some price premiums. For FCEV, the fuel cell and buffer battery causes the additional payment, for BEV, the larger battery is responsible for the additional investment. CHV have a higher investment due to hybridization and the pantograph which connects to the catenaries. The consumption is in a comparable range for diesel, LNG and hydrogen, about half for BEVs and about 60 % of a diesel drive train for CHV when driven in electric mode. The cost for operations and maintenance is based on the cost for diesel vehicles taken from [Lastauto Omnibus Katalog 2014] and adapted using the methodology in [Propfe et al. 2012] to estimate the lifetimes of different components and their related cost. This leads to a lower O&M cost for FCEV and BEV which is dominated by the cost for fuel cell and battery as the cost for IC engine and transmission are much lower or non-existent. We also have a lower cost for CHV since it doesn't contain a battery compared to a BEV and the only additional cost is cause by the deterioration of the pantograph. Ranges are only shown if they are lower than 800 km. This is the case for FCEV and BEV since we assumed the vehicles to be of similar size as diesel vehicles and

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[1] The capabilities and limitations of modelling the purchase decision of vehicles based on TCO is discussed in detail in [Plötz et al. 2014a].

[2] An option with a battery for 100 km range instead of the diesel drive train was tested in [Wietschel et al. 2017] as well, yet the range was not sufficient for the trips apart from the catenary.

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Table 2. Techno-economical assumptions for comparison.

Attribute	Unit	Diesel	LNG	Hydrogen (FCEV)	BEV	CHVCHV
Investment	EUR	128,673 (1)	195,910 (2)	174,000 (1)	185,177 (3)	152,000 (4)
Consumption	kWh/km	2.46 (5)	2.78 (2)	2.25 (5)	1.23 (1)	1.60 (6)
O&M	EUR/km	0.143 (7)	0.143 (8)	0.137 (8)	0.126 (8)	0.107 (8)
Range (if lower than 800 km)	km	–	–	400	175	–
CO_2 emission (9)	kg CO_2/kWh	0.324	0.242	0.306	0.202	0.196

(1) Hülsmann et al. 2014, (2) Kreyenberg et al. 2015, (3) Lastauto Omnibus Katalog 2013, Hülsmann et al. 2014, Thielmann et al. 2015, (4) Wietschel et al. 2016a, (5) HBEFA 3.1, (6) in electric mode: Kreyenberg et al. 2015, Wietschel et al. 2016a, (7) Lastauto Omnibus Katalog 2014, (8) Own calculations based on: (Lastauto Omnibus Katalog 2013, Propfe et al. 2012), (9) DLSV 2013, S. 28.

Table 3. General assumptions for comparison.

Parameters (all prices w/o VAT in EUR_{2016})	Unit	Value 2030	Reference
Battery price	EUR/kWh	186	(1)
Battery life time	Full cycles	5,000	(2)
Diesel price	EUR/l	1.53	(3)
	EUR/kWh	0.15	
Natural gas price	EUR/kg	1.48	(4)
	EUR/kWh	0.11	
Hydrogen price	EUR/kg	6.65	(5)
	EUR/kWh	0.20	
Electricity price commercial	EUR/kWh	0.22	(6)
Electricity price industrial	EUR/kWh	0.16	(6)
Average CO_2 emissions of German power plants	t CO_2/MWh	0.192	(7)

(1) Thielmann et al. 2015; (2) Wietschel et al. 2016a; (3) Schade und Wietschel 2016, MWV 2016; (4) Schade und Wietschel 2016, Njumaen 2016; (5) McKinsey et al. 2011; (6) Auf der Maur et al. 2015; (7) Calculations based on BMUB 2015.

the drive trains to not cause any weight or volume reduction. We will discuss this matter in the results. The CO_2 emissions are given in kg CO_2 per kWh. All alternative fuel emissions are given as fuels produced from electricity and evaluated with the average emissions of the electricity mix in 2030 explained in the following. For FCEV a well to tank efficiency of 66 %, for BEV a loss of 5 % in the low voltage grid for CHV a loss of 3 % at the medium voltage grid is assumed in 2030. CO_2 emissions differ by a factor of three between diesel vehicles and BEV or CHV. Furthermore, we need assumptions for fuel and battery prices, battery lifetime and CO_2 emissions of the German power plants in 2030 which are shown in Table 3.

The battery life time determines the number of full cycles after which a battery has to be replaced for economical purposes. This is an important aspect for the O&M cost of BEV. We assume 5,000 full cycles to be the lower bound until 2030 based on [Wietschel et al. 2016a]. The fuel and natural gas prices are taken from [Schade and Wietschel 2016], yet the current reduction of energy taxes for natural gas is neglected. The hydrogen price is taken from [McKinsey et al. 2011] and commercial (BEV) and industrial (CHV) electricity prices are gathered from [Auf der Maur et al. 2015]. The average CO_2 emissions stem from a simulation of the electricity mix in 2030 based on KS95 in [BMUB 2015]. It aims at reaching the 95 % CO_2 reduction until 2050 compared to 1990 and share of renewable energies on the electricity production is 50 %.

For CHV, we need some additional assumptions since they can only drive with electricity if they are connected to the overhead cable. Thus, we need to know if the heavy duty vehicle is driving on a highway and if this highway is retrofitted with catenaries. Since we do not have geographical information about the driving of the vehicles, we make two simplifications for these aspects. Based on [KiD 2010] we use a non-linear fit for the share of kilometres on a highway s_h based on their daily vehicle kilometres travelled dVKT, $s_h = 1 - \exp(-\mathrm{dVKT}/L_0)$ with $L_0 = 127.25$ retrieved from [KiD 2010] with least squares method.[3] For the share of driving on a highway that is equipped with catenaries, we assume that at first those highways that are most often frequented by heavy duty vehicles are first retrofitted. Figure 2 shows the share of mileage of heavy duty vehicles s_m over the share of highway kilometres ordered by their usage based on [Wietschel et al. 2017]. So, if the most frequented 20 % of highways had catenaries, almost 50 % of the mileage of heavy duty vehicles would be electrified. In this analysis, we assume that 2,000 km or 17 % of the German highway network are equipped with catenaries and thus s_m=39 %. The product of s_h and s_m results in s_e. The cost for the catenary infrastructure is estimated to be EUR 2.2 m/km [Wietschel et al. 2017].

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[3] See [Wietschel et al. 2017] for details.

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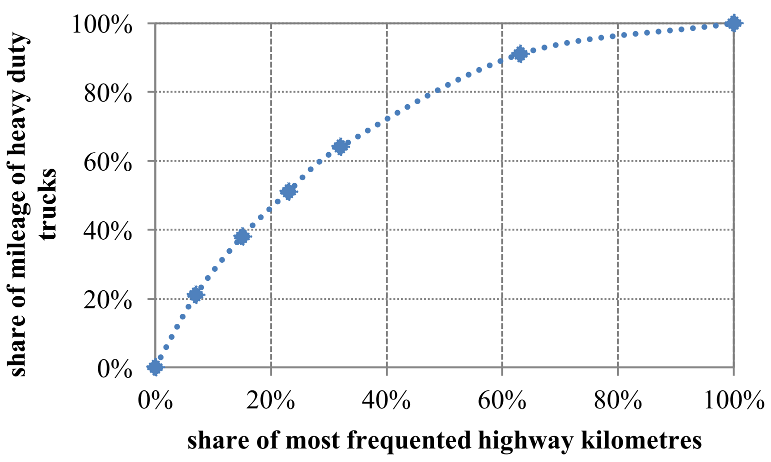

Figure 2. Share of mileage of heavy duty trucks over share of most frequented highway kilometres. Source: Own compilation based on [Wietschel et al. 2017].

Table 4. Technological readiness level of alternative drive trains.

	Diesel	LNG	Hydrogen (FCEV)	BEV	CHV
Readiness level	TRL9	TRL9	TRL5	TRL5	TRL6

Results

TECHNOLOGICAL COMPARISON

As we already saw in the assumptions section, the energy consumption of drive trains differs largely. Since we only consider the production of fuels based on renewable electricity, there are several losses in the energy conversions that have to be considered. Drive trains that do not use a combustion process are much more energy efficient than those with internal combustion. Thus, the first three drive trains are all in the same range for tank-to-wheel (TtW) efficiency while FCEV, BEV and CHV consume considerably less. The large difference between FCEV and BEV is due to the efficiency loss in the fuel cell while the difference between BEV and CHV (electric mode) results from the losses from catenary via pantograph to electric motor.

Next, we compare the technological readiness level (TRL) of the different drive trains. Only diesel and LNG vehicles are currently available for sale at the moment, thus they have the highest TRL. For CHV, some heavy duty vehicles are tested in relevant environments at the moment in Sweden, Germany and the US while FCEV and BEV are not in a demonstration project for heavy duty trucks. This is summed up in the Table 4.

Lastly, we have to mention that assumed ranges for BEV and FCEV do not meet the requirements for long-haul trucks in logistics. With the 400 km of the FCEV, about 30 % of heavy duty vehicles could perform all their daily trips without refueling during the day while the BEV-range of 175 km can only meet the needs of 2–3 % of the vehicles. Both ranges could be increased, but additional hydrogen tanks need additional volume and additional batteries require extra weight.[4] While more volume is possible through EU directive 2015/719 which permits to increase the length of heavy duty vehicles with alternative fuels by 50 cm, the issue of the weight for the battery, but also an option to recharge quickly during the day is not in sight at the moment. Furthermore, both range increases come with additional cost and we see the narrow ranges in the following already.

COST COMPARISON

The cost comparison of the five propulsion systems is performed for the two quartiles of the annual VKT distribution in [KiD 2010]. Results for the 25 %-quartile (81,492 km) are shown on the left and for the 75 %-quartile (141,777 km) on the right panel of Figure 3. Both graphs use the same display and show the cost for capital, operations & maintenance and fuel.

On the left panel, we find that BEV and CHV have almost similar decision relevant driving cost to diesel vehicles while LNG vehicles and FCEV have a significantly higher cost (10–25 % higher). For longer distances on the right panel, vehicles that are directly powered by electricity (BEV and CHV) can have lower cost than diesel vehicles, while LNG vehicles are comparable to diesel. FCEV still have an additional cost of €0.13/km compared to diesel vehicles. The compatibility for LNG vehicles, BEV and CHV with higher mileage can be explained by the lower operating cost and higher investments compared to diesel vehicles which can pay off with more driving. In the case for q75, the capital cost only makes up one quarter of the decision relevant cost and the difference in operating expenditure plays a bigger role. Thus, for FCEV to become competitive, either a decrease of the hydrogen price of 20–25 % is needed or a higher efficiency of the drive train. However, one has to keep in mind that firstly, BEV would have to be recharched multiple times during the day at short times and for CHV, a catenary infrastructure would have to be in place.

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[4] Also additional hydrogen tanks come with extra weight and batteries need more volume, but these are of secondary importance.

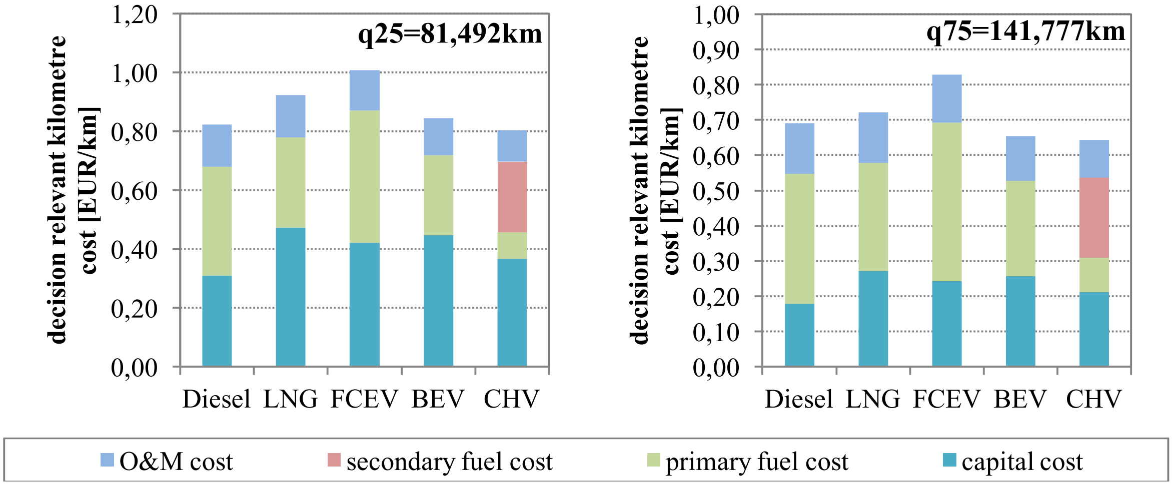

Figure 3. Cost comparison of different drive trains for heavy duty vehicles. Comparison of decision relevant cost for different annual vehicle kilometres travelled.

This leads us to a short discussion of refuelling infrastructure of the different drive trains. For LNG powered vehicles, the infrastructure is more complex since LNG has to be cooled or compressed and thus the investment for LNG refuelling stations would be higher. Even more complex is the infrastructure for hydrogen which has often been discussed for passenger cars already.[5] However, heavy duty vehicles would need more hydrogen per refuelling occurrence and would have to be faster than for passenger cars, so the trucks do not spend too much time at the refuelling station. This implies an increased cost for refuelling stations for truck FCEV compared to those for passenger cars. For BEV, the question is even more complex. To this point, most of the fast charging stations in Germany have 50 kW which would take more than three hours to recharge the 160 kWh battery. The question is whether there will be refuelling stations in the future that allow a 5–10 min recharging at 1–2 MW and if there are batteries available to be recharged with that power. Lastly, the infrastructure for CHV is well known from trains and trams in cities and even some buses with catenary exist. However, a significant amount of catenaries has to be set up to be usable for CHV at a large cost.

Thus, summing up this qualitative discussion of infrastructure cost, we may say that a LNG infrastructure is somewhat more expensive than the one for diesel and the infrastructure for FCEV, CHV is much more expensive. For BEV, we cannot think of an adequate solution at the moment.

ENVIRONMENTAL PERSPECTIVE

From an environmental perspective, we compare the specific CO_2 emissions for all drive trains and the renewable electricity that would be needed to completely power all heavy duty trucks. It has to be kept in mind that the CO_2 emission and cost calculations are based on an average electricity mix in Germany. The results for the specific CO_2 emissions are displayed in Figure 4.

We find emissions of about 800 g CO_2/km for diesel vehicles. The same holds for LNG and hydrogen. However, FCEV have a relatively high CO_2 emissions per kilometres (85 % of diesel) if the electricity mix is considered for its production. The best solution from an emissions point of view would be to use electricity in BEV which are significantly lower even if powered with the electricity mix (192 g CO_2/kWh). For CHV, we find a 25 % lower CO_2 emission than for diesel vehicles. These stay about equal for short and longer distances and could only be raised with a higher amount of catenary infrastructure.

In Figure 5, we show the (renewable) electricity needed if all German heavy duty trucks would be replaced by vehicles of the observed propulsion technology. For this analysis, we assume that the WtT efficiency for the conversion from electricity to LNG is 41 %. We find large differences between the technical options. While we would need about 130 TWh per year additional electricity for LNG, it would take 55 TWh for FCEV, 25–30 TWh for BEV and CHV. However, for the latter it is assumed that these vehicles perform their driving completely in electric mode which is not possible if only highways were covered with catenaries. Still, this shows the large amount of energy needed for a complete replacement of 40 t diesel trucks with one fuel, e.g. when compared to the total annual German electricity consumption of 500 TWh in 2016.

SYNTHESIS OF RESULTS

The results from the previous sections showed several aspects that could be considered for a comparison of alternative fuels for heavy duty vehicles. These were of technical, economical and environmental nature. A qualitative summary of these results is shown in Table 5. Here, we put “0” if the drive train is equal to a diesel vehicle in the category, “+” if it is better and “++” if it is much better. If it is worse than a diesel vehicle, we put “-” and if it is much worse we take “--”.

We observe that LNG is the technically closest solution at the moment that does not need a lot of adaption for users and refuelling stations. LNG has lower CO_2 emissions than diesel as fuel for heavy duty vehicles and vehicles are already available for sale. However, LNG has some disadvantages concerning

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5. See [Gnann and Plötz 2015] for an overview.

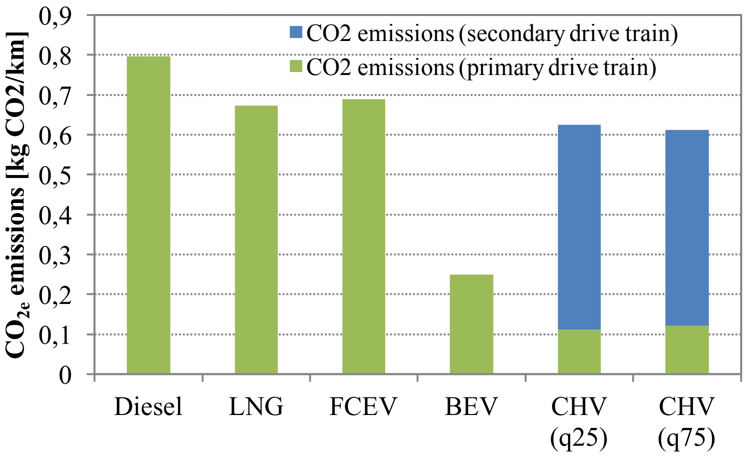

Figure 4. Specific CO_2 emissions for different drive trains on the left panel and total annual renewable energy needed for a complete replacement of all heavy duty vehicles with this fuel on the right panel.

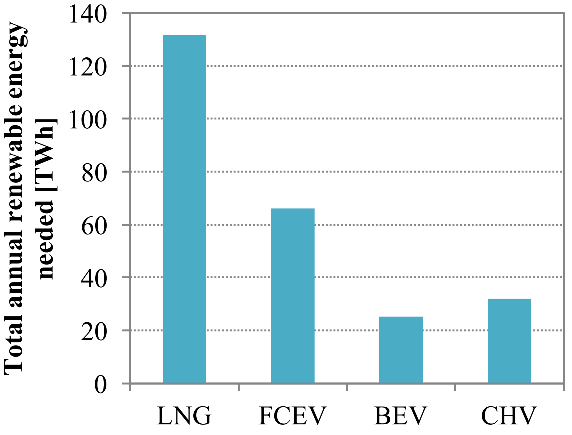

Figure 5. Total annual renewable energy needed for a complete replacement of all heavy duty vehicles with this fuel on the right panel.

Table 5. Summary of comparison of alternatives.

Measure	Diesel	LNG	FCEV	(BEV)	CHV
Readiness level	0	0	--	--	-
WtW efficiency	0	-	+	++	++
Decision relevant operating cost	0	-	--	++	+
Infrastructure cost	0	-	--	--	--
CO_2 emission	0	+	+	++	+
Renewable energy needed	0	--	0	++	++

vehicle cost, infrastructure cost and especially WtW efficiency. FCEV could be one future solution with several benefits compared to diesel vehicles as the WtW efficiency is higher and CO_2 emission is lower, even if it is powered with the electricity mix. The main obstacles are the high decision relevant cost (hydrogen price or higher efficiency) and the high cost for refuelling infrastructure. BEV would be the preferred solution from a CO_2 emission, renewable energy needed and WtW efficiency point of view. However, with current technologies, their range is considered inadequate except with more battery capacity which significantly reduces the load for transported goods, or a charging infrastructure with power levels that are currently researched. Both options are not in sight at the moment. Lastly, CHV offer a solution with several advantages: low renewable energy needed for a complete replacement, lower CO_2 emission, a high WtW efficiency and a compatible decision relevant operating cost. Yet, the infrastructure cost is high and determines the CO_2 emission reduction largely.

Discussion and conclusions

This comparison of alternative drive trains for heavy duty vehicles is based on a variety of assumptions for Germany in 2030. While the costs for vehicles might differ largely and are highly uncertain, more important are the assumptions for the efficiency of drive trains and the fuel costs which determine the decision relevant cost. All these parameters were taken from literature and discussed in detail [Wietschel et al. 2016a]. Furthermore, we only looked at heavy duty vehicles with a total allowed weight of 40 tons. If some of the technologies diffuse into smaller vehicle size classes or passenger cars, there might be some synergy effects, especially on fuel prices which have been neglected here. There might also be a variety of fuels used in the long term, e.g. BEV for short-haul and CHV or FCEV for long-haul vehicles, yet we assume that a large infrastructure investment will only be useful for one or two propulsion technologies.

We did not discuss all options for fuels that could be considered for the transport sector. Biofuels would also be possible to be compared, but the competition with food production rules out all first-grade biofuels (purposely planted) and second-grade biofuels (waste) may be needed in the aviation sector. Methanol produced from renewable energies could be a cost efficient short- to medium-term solution. However, from renewably produced hydrogen, another conversion step to methanol production is needed which includes an energy loss of about 32 % [Räuchle et al. 2016] and, more important, methanol would locally not be emission free.

One important question is, if policy makers and industry can agree on a long-term solution or are more short- to medium-term focussed. In the short to medium term, methanol or LNG could be solutions that are technologically ready and may be competitive soon, especially if methanol is produced in areas with low electricity prices and imported to Germany. However, both solutions have local emissions that may not help for a long-term emission free transport, especially because of their WtW efficiency. If the goal is to reduce emissions from transport completely then FCEV, BEV or CHV seem to be the only solutions for a (nearly) locally emission-free transport and a tremendous CO_2 emission reduction, if the electricity is produced via renewables. Each will require an investment in refuelling infrastructure that is probably higher for CHV, yet the additional energy needed for FCEV requires investment in more renewable energy production. Certainly, more research is needed for each of these options, before an evidence-based decision can be made.

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