RESEARCH

Fuel Cell Drive for Urban Freight Transport in Comparison to Diesel and Battery Electric Drives – a Case Study of the Food Retailing Industry in Berlin

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Abstract

The option of decarbonizing urban freight transport using Battery Electric Vehicle (BEV) seems promising. However, there is currently a strong debate whether Fuel Cell Electric Vehicle (FCEV) might be the better solution. The question arises as to how a fleet of FCEV influences the operating cost, the Greenhouse Gas (GHG) emissions and primary energy demand in comparison to BEVs and to Internal Combustion Engine Vehicle (ICEV). To investigate this, we simulate the urban food retailing as a representative share of urban freight transport using a multi-agent transport simulation software. Synthetic routes as well as fleet size and composition are determined by solving a Vehicle Routing Problem (VRP). We compute the operating costs using a total cost of ownership (Total Cost of Ownership (TCO)) analysis and the use phase emissions as well as primary energy demand using the Well To Wheel (WTW) approach. While a change to BEV results in 17 - 23% higher costs compared to ICEV, using FCEVs leads to 22 - 57% higher costs. Assuming today's electricity mix, we show a GHG emission reduction of 25% compared to the ICEV base case when using BEV. Current hydrogen production leads to a GHG reduction of 33% when using FCEV which however cannot be scaled to larger fleets. Using current electricity in electrolysis will increase GHG emission by 60% compared to the base case. Assuming 100% renewable electricity for charging and hydrogen production, the reduction from FCEVs rises to 73% and from BEV to 92%. The primary energy requirement for BEV is in all cases lower and for higher compared to the base case. We conclude that while FCEV have a slightly higher GHG savings potential with current hydrogen, BEV are the favored technology for urban freight transport from an economic and ecological point of view, considering the increasing shares of renewable energies in the grid mix.

Keywords: urban freight transport; multi agent; vehicle routing problem; decarbonization; fuel cell electric vehicles; well to wheel; total cost of ownership

1 Introduction and Motivation

Commercial road vehicles including buses cause 35.6% of all greenhouse gas (GHG) emissions in the German transport sector. In order to achieve the climate protection goals in this sector, GHG emissions must be reduced through alternative vehicle drive systems [1]. The current focus is on battery electric vehicles (BEV) due to the complete avoidance of local emissions and a comparably high efficiency [2, 3]. However, vehicles powered by Fuel Cell (FC) can be an alternative solution solving several issues of BEV [4]. In addition to locally emission-free driving, fuel cell electric vehicles (FCEV) offer the advantages of a short refueling time of only a few minutes and a diesel-equivalent range [5]. By converting urban freight transport from ICEV to FCEV, delivery routes, loading and refueling times can be maintained. In contrast, BEVs have range constraints due to the conflict between payload and battery size and require charging times of up to several hours [6]. The question this paper intends to answer is whether these advantages are sufficient to make FCEV advantageous over BEV in decarbonizing urban transport, despite their lower overall efficiency.

1.1 Technical requirements

Currently, there are mainly prototypes of FC trucks. These include light 7.5t trucks such as the Fuso Vision F-Cell or heavy-duty semitrailer tractors such as the Nikola Motors Tre, which is expected to be ready for series production by 2023 [7, 8]. According to [9], fuel cells in buses have already reached a lifetime of 25,000 operating hours. This is expected to be sufficient for most trucks to avoid an expensive change of the FC. FC trucks usually store gaseous hydrogen using pressure tanks of type 3 [10] with comparably low pressure of up to 350 bar. Therefore pre-cooling of the hydrogen is unnecessary [11]. There are many ways to produce hydrogen using fossil and renewable energy sources. Today, 54% of hydrogen in Germany is produced as a by-product of other production processes and 46% is produced by steam reforming of natural gas [12]. Regenerative hydrogen production can be implemented, for example, with Power-to-Gas (Power To Gas (PtG)) plants [5]. There are currently 86 gas stations in Germany (as of August 2020) for FCEV refueling. Six of them offer hydrogen pressure of 350 bar and are therefore compatible for fuel cell buses and trucks [13].

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1.2 State of research

Several studies have already examined the conversion from diesel to FC trucks: The "Mobility and Fuel Strategy of the Federal Government " [9] examined the research and development needs of FC trucks. The study carried out a market and technology analysis for Germany. The aim of the model is to test the potential market uptake of alternative drive systems. General conditions such as vehicle class, type of drive, infrastructure, traffic volume and general data such as development of freight traffic or energy scenarios are considered. The model depicts the purchasing decisions of truck operators, taking into account different types of truck usage. The study calculates total cost of ownership (TCO) and well-to-wheel (WTW) emissions for each truck class and drive type. Other studies that consider FCEV for a future market uptake are [14, 15, 16, 17]. Yazdanie et al. analyze the WTW emissions and primary energy demand of ICEVs, BEVs, hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV) and FCEVs of passenger cars considering fossil energy and renewable energy sources [18]. They determine the consumption values per km for the different types of drive, and the emissions and energy requirements of the different vehicle types. Lombardi et al. present a performance comparison and the

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ecological effects of four truck classes and the types BEV, ICEV, PHEV and Plug-in FCEV [19]. They use a rule-based and optimized consumption model based on the pontryagin minimum principle. Using two different synthetic drive cycles they calculate the WTW GHG emissions and the WTW primary energy demand using the consumption values. Transport and distribution are taken into account in the WTW path. Lee et al. compare the primary energy consumption and WTW emissions of FCEV and ICEV trucks [20]. A high-resolution longitudinal dynamics model and real vehicle measurements generate the necessary data. For hydrogen production, they consider steam reforming with natural gas and hydrogen as fuel in liquid and gaseous form. Further studies that investigate different hydrogen production paths are [21, 22, 23, 24, 25, 26]. Daneberg investigates the potentials of FC trucks, their TCO, hydrogen costs, and the infrastructure required for the Oslo-Trondheim route [27]. The author uses a case study to determine the economically most suitable case depending on hydrogen costs and fleet size. Hall and Lutsey deal with the TCO for zero-emission trucks for the Los Angeles area, California [28]. They investigate the costs and number of hydrogen filling stations for low, medium and high fleet compositions for long-haul tractor-trailers, port drayage, and local delivery trucks. Further studies that investigate the costs of FCEVs are [29, 30, 31, 32, 33]. The summary of the current state of research shows that the topic of fuel cell drive has already been investigated in market ramp-up models [9, 14, 15, 16, 17], the conversion of car traffic to alternative drive systems [18], the environmental impact of individual vehicles and production paths [19, 20, 21, 22, 23, 24, 25, 26, 34], and infrastructure and operating costs of trucks [27, 28]. However, there is no study that examines the effects of a complete conversion of the entire urban logistics sector to FC trucks. Changes in costs, emissions, and primary energy demand are still pending, especially taking into account the influence of current and future hydrogen production and system prices. Furthermore, to the best of our knowledge, prototype FC trucks have not been used as reference vehicles so far. Martins-Turner et al. use the transport simulation MATSim to investigate the usability of BEVs in comparison to ICEVs for urban freight transport using the food retailing logistics in Berlin as a case study [35]. Changes in transport costs, WTW emissions and primary energy demand of ICEVs and BEVs are computed and compared. Since no such study for FCEVs exits so far, the following research question arises: Can FCEVs outperform BEVs in terms of TCO, WTW emissions and primary energy demand when considering a complete decarbonization of urban freight transport?

2 Methodology

To find an answer to the research question posed, this study applies the following methodology, which is divided into supply planning, simulation of freight transport, TCO, and well-to-wheel analysis, to the use case of delivering goods to food retailing stores in Berlin.

2.1 Tour planning

To deliver food to the various sales locations, nearby distribution centers (so-called "hubs" or “depots”) are first supplied. From there the goods are distributed further to the retail stores. Due to its focus on urban transport, this study considers the latter. Since no data about the actual routes are available, a Vehicle Routing Problem (VRP) with a cost-based objective function is solved using the open-source software jsprit [36]. This provides a plan of the delivery routes as well as a certain fleet composition at minimal cost. Internal and external factors are taken into account. Internal factors are the location of the hubs and the available vehicle types which differ in variable and fixed costs (determined using TCO) and maximum capacity. External factors such as demand for goods, delivery location, and the time windows for delivery are decisive for solving the VRP. They are taken from [37], which is also the basis of [35]. Also, the transport network and the traffic are external factors that are taken into account.

2.2 Simulation of freight transport

To simulate the different cases for urban freight traffic, the openly available, agent-based simulation software MATSim [38] is used. MATSim simulates each vehicle of the transport system as a so-called agent in a transport network, whereby various activities such as receiving and delivering goods are carried out. With this simulation setup, the scenario of urban freight traffic with FCEV can be implemented. In this study the Open Berlin scenario is used [39]. After 10,000 iterations of the VRP solver, a single MATSim simulation for one day is performed. Subsequently, the costs and calculated fleet composition are examined and the distance and travel times covered by the vehicles are retrieved. The energy demand of the fleets is calculated from the driven distances and the vehicle class specific consumption values. Using the GHG emissions and primary energy factors multiplied by the hydrogen demand, the total GHG emissions and the energy demand for the different fuels of WTW can be compared.

2.3 Total Cost of Ownership (TCO)

In order to determine the variable and fixed costs for the fleet composition, the life cycle costs are investigated. One method to analyze these costs is the TCO. Fixed costs such as acquisition costs and variable costs such as operating costs of the product are considered [40]. This allows the comparison of the different drive types in terms of operational costs over the product life cycle. In this paper, the TCO method according to the "Bundesverkehrswegeplan 2030" (BVWP, Federal Transportation Plan) [41] is established for FCEV as already done for BEVs and ICEVs in [35]. Four truck classes are considered: light (7.5 tons), medium (18 tons), heavy (26 tons), and heavy (40 tons). For the 40 tons trucks, trailers are included in the cost calculation. The purchase price of the trucks is depreciated half by time and half by kilometers driven. In cost accounting according to BVWP, no insurance costs or other taxes are considered. However, from a supplier's business point of view, these costs are important to consider. Therefore, corresponding values from [37] are used. BEVs and FCEVs are expected to have lower maintenance costs than ICEVs due to fewer components installed. However, there are no concrete values yet. Therefore, the maintenance costs from [37] are used for all drive classes.

2.4 Well to Wheel Analysis (WTW)

The WTW analysis describes the energy paths of energy carriers from the source to the wheel, distinguishing between Well To Tank (WTT) and Tank To Wheel (TTW). The TTW path accounts for the expended energy and the associated GHG emissions in the steps required to deliver the energy carrier to the vehicle. The ecoinvent 3.6. Cutoff Unit database serves as a basis to model the processes and flows for the WTT analysis of the respective energy carriers [42]. For better comparability of the energy sources from the ecoinvent database and the data from [43], the lower heating value was taken into account as a basis. For BEVs and FCEVs the TTW path equals zero, as no emissions arise due to the energy conversion within the vehicles. For the ICEVs, the energy path for a TTW analysis is derived from the consumption values of the trucks and an emission factor for the burned diesel [44]. The GHG emissions and energy use are calculated according to the impact assessment methods IPCC 2013 GWP 100a and Cumulative Energy Demand for lower heating value.

3 Case study

This case study is based on [35] in which the food retailing logistics in Berlin is modeled using ICEV and BEV. This study adds FCEV to the scope of observation and combines all results to obtain a holistic perspective. Since the demand model in [35] is based on [37], this study relies on the same model for comparability. Following [37], there are 1057 food markets in Berlin that place approximately 1928 inquiries for goods per day. These inquiries are served by 15 food suppliers (carriers) with 17 distribution centers. The goods are divided into the categories fresh, frozen and dry, which are handled separately. Technically, this leads to 45 carriers that have to be considered in the VRP. The loading time per pallet is approximated with 3 minutes. It is possible that the trucks can be loaded several times at the depots. Not all vehicle sizes are available to all carriers [37]. However, the suppliers have the possibility to select any number of available trucks for their fleet.

3.1 Vehicle Parameters

In this study, the five different cases shown in Figure 1 are analyzed. First, the current state is modeled as a reference. For this purpose, four types of ICEVs in the dimensions 7.5t, 18t, 26t and 40t are considered. Subsequently, two cases are considered for the BEV. Martins-Turner et al. show that today a BEV excluding battery costs about 1.6 times as much as a complete ICEV [35]. However, it is assumed that in the future a BEV without a battery will cost the same as an ICEV. These are the two case distinctions for vehicle costs (BEV160 and BEV100). In this study it is assumed that BEV160 represents today's market and will therefore be operated with today's electricity mix. In contrast, BEV100 represents a future scenario and is therefore operated with an electricity mix of 50% wind and 50% solar power. BEVs are designed in the same weight classes as the ICEVs. The batteries are dimensioned in such a way that, taking into account the increased permissible total mass for emission-free commercial vehicles in the EU [45], there is no change in payload compared to ICEVs. Lithium nickel manganese cobalt oxides (NMC) commercial vehicle batteries with a price of 600€/kWh on pack level are used. All other specifications for the first three cases can be viewed in [35]. The novelty in this study are the two cases with FCEV. The layout of FCEV is equivalent to BEV, but with a smaller battery and the FC and tanks as additional components. Therefore the cases FCEV160 and FCEV100 are defined analogously to the BEV cases.

As there are currently no FC trucks in series production, the Nikola Tre [8] for the 40t truck, the prototype from the partner project ASKO Scania [46] for the 26t truck and the concept truck Fuso Vision F-Cell [7] for the light 7.5t truck are selected as reference models. FCEV prototypes for the medium 18t truck are still pending, therefore separate assumptions are made. FCEVs have an approximately 1.8 times higher TTW consumption due to the energy conversion in the FC for which an efficiency of 55% is assumed according to [19]. According to Kurzweil the FC of a vehicle is mostly kept at an optimal operating point and the remaining power is provided by a battery [47]. Thus the consumption value of the 18t truck can be calculated with the consumption value of the BEV in the same weight class divided by a fuel cell efficiency of 55% [19]. The consumption values for the 7.5t, the 26t and the 40t truck result from the range and stored energy in the form of hydrogen indicated in [7, 8, 46]. The values appear plausible, as similar values result with the aforementioned calculation method. For all FCEV classes, the same system power as in the BEV case is assumed in order to be able to compare them fairly. In FCEV, the system performance is made up of the power of the fuel cell and the battery. The hydrogen

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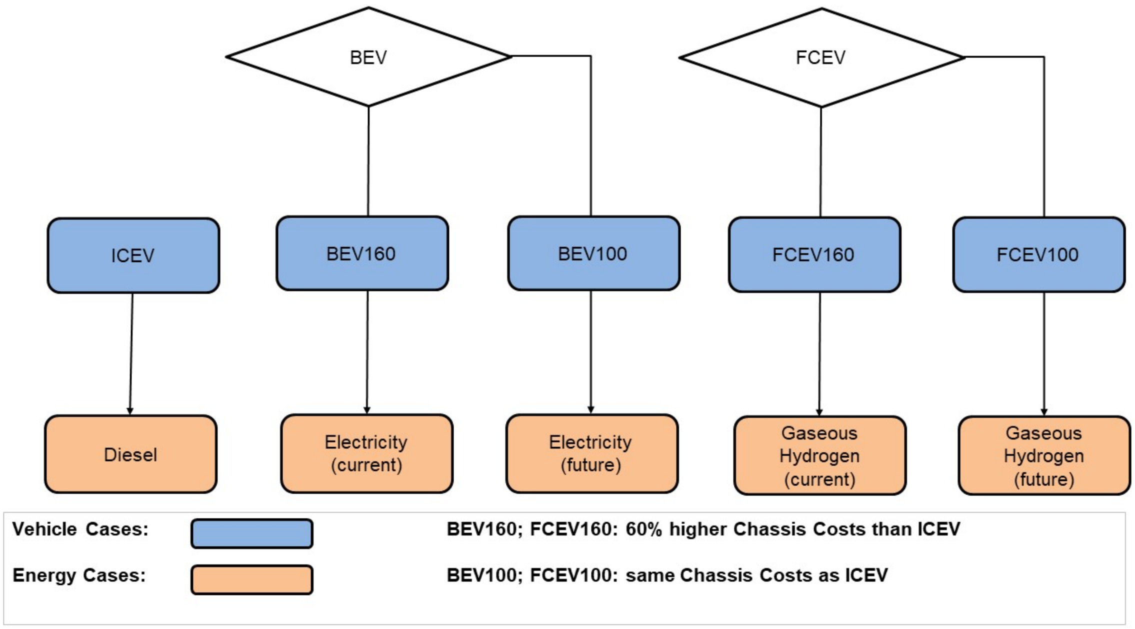

Figure 1 Overview of Vehicle and Fuel Scenarios

tank of the 18 tons FCEV is dimensioned to achieve a similar range as for ICEVs. For the FCEV cases, the vehicle configurations in table 1 result. The simulation results in figure 2 shows that the assumed ranges of the FCEVs are sufficiently high for all truck classes so no intermediate refueling is needed.

3.2 Cost Parameters

3.2.1 Vehicle Prices

Since the construction of BEV and FCEV are very similar except for fuel cell and tank, the same chassis costs presented in [35] are assumed for both vehicle types. It is assumed that the chassis costs for FCEV are currently 60% higher than for ICEV (Case: FCEV160) and are expected to be the same as for ICEV in the future (Case: FCEV100). The cost factors hydrogen tank, fuel cell and battery are included in the purchase price of the FCEV in addition to the chassis costs. Specific costs for compressed gas tank, fuel cell and battery are assumed to be 36.68€/kWh, 205€/kW and 600€/kWh [35, 48]. Table 2 shows the cost structure for all cases.

The lifetime of the fuel cell is critical for trucks, because they are exposed to a longer daily operation compared to passenger cars. Since in jsprit every vehicle is assigned to a specific driver and the drivers are only allowed to work 8h per day according to german law, 8h is the longest possible FC operating time per day. Assuming 250 working days per year and a vehicle lifetime of 11 years, a maximum fuel cell lifetime of 22,000h is required. The assumption of 25,000h is therefore sufficient [9]. The wage costs for the drivers are covered by [41].

3.2.2 Infrastructure and Hydrogen Prices

This study is based on the assumption that the infrastructure to provide hydrogen is available. This contradicts the present situation described in the introduction with 6 capable gas stations, but is a mandatory prerequisite for a complete conversion to FCEV. It is assumed that FCEVs start their delivery routes

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Table 1 Vehicle Specifications of FCEV Classes

FCEV class	7.5 tons	18 tons	26 tons	40 tons
Comparable models	Fuso Vision F-Cell	-	ASKO Scania FCT	Nikola Motors Tre
range [km]	300	500	500	800
energy consumption [kWh/100km]	111	193	275	333
system power [kW]	210	305	370	440
fuel cell power [kW]	75	80	90	120
battery power [kW]	135	225	280	320
hydrogen fuel [kg]	10	29	33	80
battery capacity [kWh]	40	50	56	70

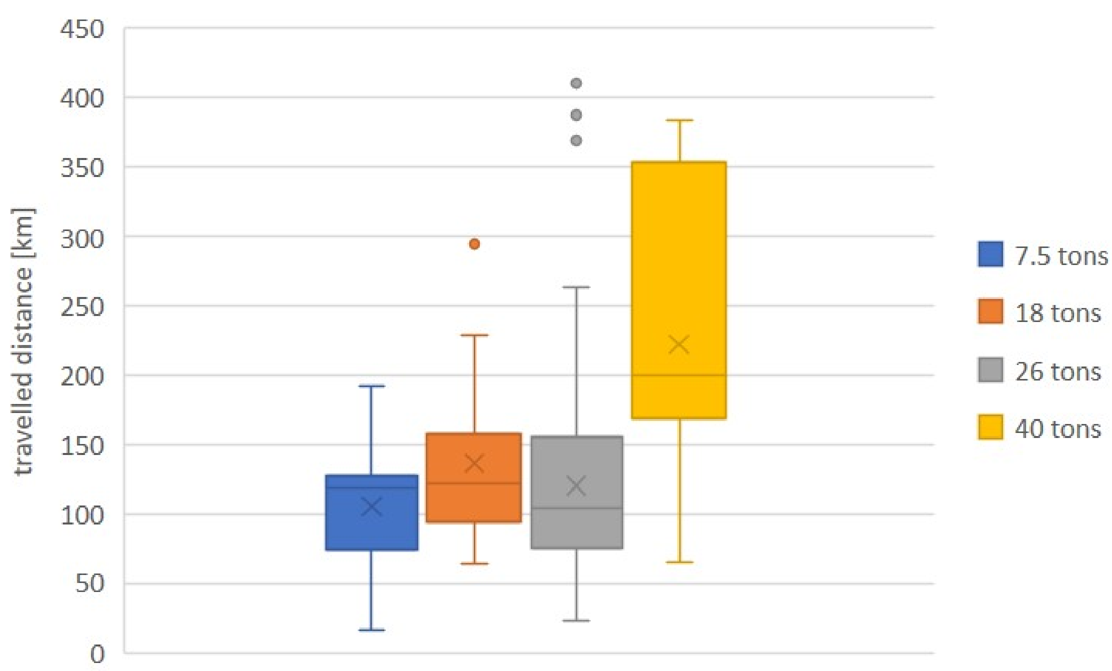

Figure 2 Calculated Driving Distances of FCEVs

Table 2 Cost Parameters for Vehicle Types

Vehicle type	Cost type	Base: ICEV	BEV 160	BEV 100	FCEV 160	FCEV 100
7.5 tons	fixed [€/day]	63.49	81.04	74.76	80.91	74.63
	variable per distance [€/km]	0.4	0.51	0.46	0.81	0.56
	variable per time [€/h]	17.64	17.64	17.64	17.64	17.64
18 tons	fixed [€/day]	80.47	107.43	96.26	109.29	98.13
	variable per distance [€/km]	0.65	0.61	0.55	1.15	0.74
	variable per time [€/h]	17.64	17.64	17.64	17.64	17.64
26 tons	fixed [€/day]	82.6	132.14	119.6	114.96	102.41
	variable per distance [€/km]	0.67	0.76	0.72	1.46	0.92
	variable per time [€/h]	17.64	17.64	17.64	17.64	17.64
40 tons	fixed [€/day]	126.58	192.8	183.93	170.94	162.07
	variable per distance [€/km]	0.69	0.8	0.78	1.67	1.04
	variable per time [€/h]	20.124	20.124	20.124	20.124	20.124

with a full tank. Refueling times are considered negligible compared to necessary loading times at the depots. Accruing infrastructure costs are not examined in detail within the scope of this study, but are integrated in the assumptions of hydrogen prices. For the FCEV160 case, which assumes the current state of the art and current prices, a hydrogen price of 13.23€/kg is assumed. This results from the case "0.1 million FCEV" from [5] where the hydrogen is transported by trucks. This study assumes a hydrogen production mix of about 50% by-products of the chemical industry and 50% natural gas reformation according to [5]. For the future FCEV100 case the hydrogen price is set to 7.13€/kg. This price results from the scenario "20 million FCEV" from [5], in which pipelines and trucks transport the hydrogen. The hydrogen is produced exclusively by electrolysis using renewable energies.

3.3 Well-To-Tank Parameters

For the base case and the two BEV cases the values from [35] were updated. For the FCEV cases different production mixes are assumed for today and the future. All emission factors can be seen in table 3. In Germany, a mixture of diesel with a maximum of 7% biodiesel is permitted according to DIN EN 590 [49]. The energy and emission factors of this diesel mix are taken from DIN EN 16258 [44]. The German electricity mix in ecoinvent is updated per share of production according to [50] for 2019 and expanded to include the production process using photovoltaics (see figure 3). The flows in ecoinvent are scaled proportionately or supplemented by individual flows from the database. In addition, a future energy mix (Electricity (future)) of 50% wind and 50% solar energy is defined as in [51]. The processes of electricity generation in Germany are accordingly adopted from ecoinvent.

The WTT consideration for hydrogen is divided into two cases: Gaseous Hydrogen (current) and Gaseous Hydrogen (future). The current case consists of the production methods according to the current status as shown in [12] as follows: 46.15% steam reforming from natural gas; 19.23% gasoline reforming; 27.69% ethylene production, 6.92% chlor-alkali electrolysis (see figure 4). The process for steam reforming from natural gas is taken from the JRC study and included in our calculations [43]. In this case it is assumed that a central upscaled reformer is used, natural gas is transported by pipeline to Europe, compressed and distributed to the retail market [43]. The other manufacturing processes for the German site are taken from ecoinvent 3.6. Cutoff Unit.

As a sensitivity analysis, a second case is calculated for today's hydrogen, which assumes that the hydrogen is produced entirely by high temperature electrolysis using today's electricity. This also serves for a better comparison with the current BEV scenario. For the efficiency of the high temperature electrolysis , a range between 65% and 85% is specified according to [52]. For simplification, the costs for this path are not changed compared to today's market price. This is not unrealistic (although somewhat low), but no real-world values are available, since high temperature electrolysis does not yet play a role in commercial hydrogen production.

The potential to produce large amounts of hydrogen from renewable energy sources in Germany is limited due to the space needed to build wind turbines or solar parks. One possible solution is PtG, which are ideal at locations with adequate available space and wind or sunshine [3]. The renewable electricity is directly usable in electrolysers to produce hydrogen. The future case consists of 50% electrolysis with wind power and 50% electrolysis with solar power (see Figure 4). The electricity generated by offshore wind turbines is used to produce hydrogen which is then distributed by pipelines to the filling stations. For generating electricity from offshore wind turbines the process from

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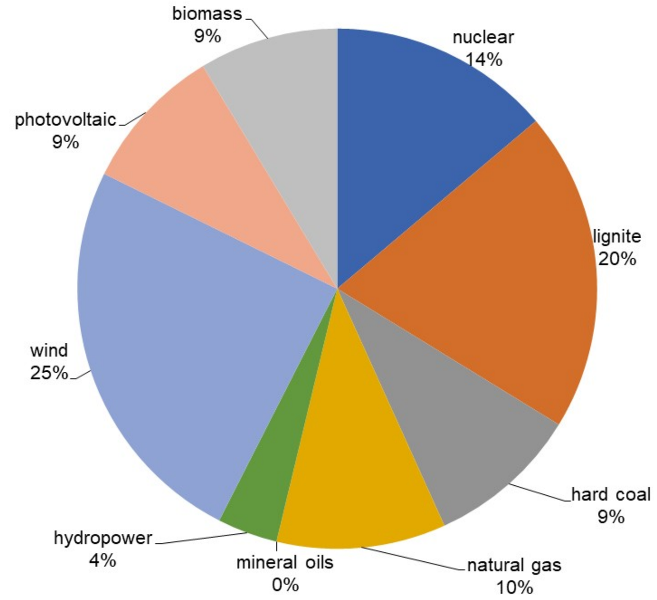

Figure 3 Electricity Mix of Germany for 2019 [50]

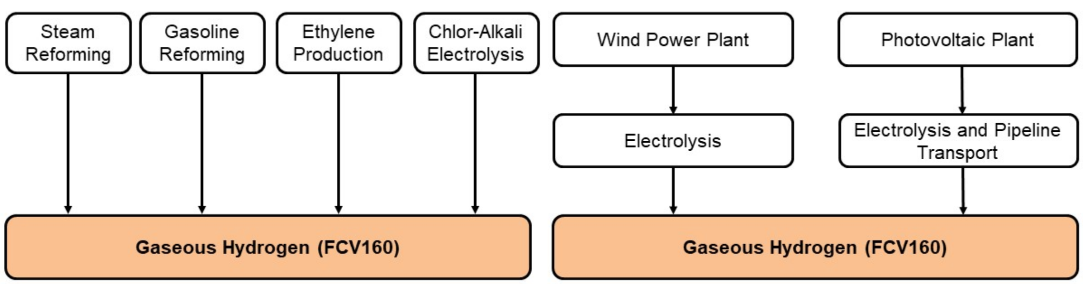

Figure 4 Composition of current Gaseous Hydrogen (FCEV160) and future Gaseous Hydrogen (FCEV100) Production

ecoinvent is used. Subsequent processes such as electrolysis, power distribution and compression on the retail side are taken from [40] and included in our calculations. The energy required for these processes results from the future energy-mix (Electricity (future)). As regions like North Africa have sunny days almost

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all year round, there is a high potential for power-to-gas plants. The electricity generated by photovoltaic systems can then be used directly to produce hydrogen. In this study it is assumed that 50% of future hydrogen will be produced in this way. Therefore, the power generation process from ecoinvent and the intermediate steps from [40] are used. According to [48] it is possible that, in addition to natural gas pipelines that have already been laid from North Africa to Europe, hydrogen pipelines could be added to the existing pipelines. It is assumed that the hydrogen will then be transported to Germany via a 4000km long pipeline.

4 Results

The results of the simulations are divided into TCO, WTW emissions and primary energy consumption of the fleets. The fleet composition which results from solving the VRP for the different cases can be seen in Figure 5. It is noticeable that the 26 tons trucks make up the largest share of all truck classes with 73 - 79%. It should also be mentioned that the BEV cases require between 1.5 - 3% less vehicles than the ICEV and FCEV cases.

Figure 6 shows the resulting driving times and distances of the entire truck fleet for all cases. In comparison to the ICEV case, both BEV cases have 1.5 - 1.9% longer travel times and 1.6 - 2.7% additional distances for the entire truck fleet.

The total costs of the fleet of all carriers per day and per technology are divided into fixed, time and distance variable costs (see Figure 7). The daily costs of the entire ICEV fleet of all carriers amount to 66,997 €/day consisting of fixed costs (24,204 €/day), time variable (18,593 €/day) and distance variable (24,200 €/day) costs. The total costs for the BEV cases are 82,751€/day (BEV160) and 78,318€/day (BEV100), which translates into an increase of 23.5% and 16.9% compared to the ICEV case. This is mainly driven by the fixed costs for BEVs, which are 38 to 49% higher than those for ICEV because of the high battery price. These also influence the distance variable cost. Since procurement costs are depreciated half by time and half by distance, the high system prices result in a slight increase of 1.6% and 2.7% compared to the base case despite the high efficiency of the powertrain. Also, the time variable costs for both BEV cases are slightly higher at 2% due to the slight increase in total travel time. The total daily costs of the FCEV cases are 105,336 €/day (FCEV160) and 82,271€/day (FCEV100) which amounts to an increase of 56.6% and 22.3% compared to the base case. The distance variable costs are the largest part with 53,111 €/day (FCEV160) and 33,369€/day (FCEV100). They are 119% and 38% higher compared to the ICEV case. This results mainly from the high hydrogen prices. In addition, the fixed costs for FCEV of 33,375 €/day (FCEV160) and 30,052 €/day (FCEV100) result in an increase of 25% and 38% compared to the base case. Figure 7 shows the absolute costs for all considered cases.

Figure 8 shows the WTW CO2 equivalent emissions per year of the entire fleet for all cases. As mentioned before, a distinction is made between electricity produced according to the current production process and electricity from 100% renewable energy sources. Hydrogen according to the current production mix, electrolysis using the current electricity mix and produced using 100% renewable energies is considered. The GHG emissions for the ICEV case amount to 9,572tCO2eq/a. 7,151tCO2eq/a result for the BEV case with the current German electricity mix, (BEV160). This is a 25% reduction of GHG emissions compared to the ICEV case. Considering a future electricity mix of 100% renewable electricity, the GHG emissions drop to 774 tCO2eq/a (BEV100). Compared to the base case, this is a reduction of 92%. The WTW emissions of the FCEV fleet with a current hydro-

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Table 3 Well-to-Tank Energy and Emissions Factors

Energy carrier	Well-to-Tank	
	Energy Factor [kWh/kWhEnergyCarrier]	Emissions Factor [kg CO2eq/kWhlEnergyCarrier]
Diesel	1.25	0.318
Electricity (current)	2.45	0.522
Electricity (future)	1.30	0.057
Gaseous Hydrogen (current)	1.64	0.258
Gaseous Hydrogen sensitivity (current electricity, $\eta = 85\%$)	2.88	0.61
Gaseous Hydrogen (future)	2.42	0.103

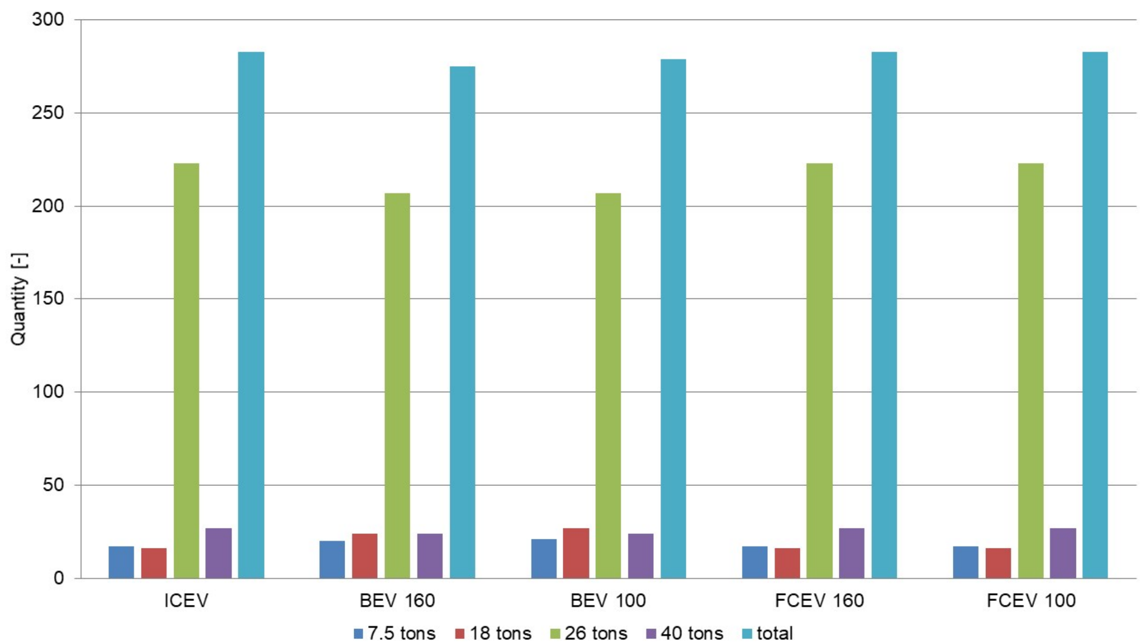

Figure 5 Resulting Fleet Composition

gen mix are 6,442 t CO2eq/a. This corresponds to a 33% reduction in GHG emissions compared to the ICEV case. However, the sensitivity analysis results in 15.338tCO2eq/a (85% electrolysis efficiency) for hydrogen from the current electricity mix, which is a 60% increase in emissions compared to the ICEV case. If the FCEV fleet is operated with a 100% renewable hydrogen mix (FCEV100), the result is 2,580tCO2eq/a. This represents a 73% reduction in emissions compared to the ICEV case.

Figure 9 shows the primary energy demand per year for all cases. All primary energy factors used are shown in Table 3. The primary energy demand for the ICEV case with 37,680 MWh/a is the basis for comparison. The primary energy demand for the BEV case with the current electricity mix is 33,562 MWh/a (BEV160). Compared to the ICEV case, this is about 11% less primary energy. With an electricity mix of 100% renewable electricity, 17,715 MWh/a (BEV100) is required. This corresponds to a 53% reduction in primary energy demand. Considering the entire FCEV fleet, the primary energy requirement is 40,960 MWh/a with the current hydrogen mix, 71,989 MWh/a for the hydrogen produced using the current electricity mix and 60,441

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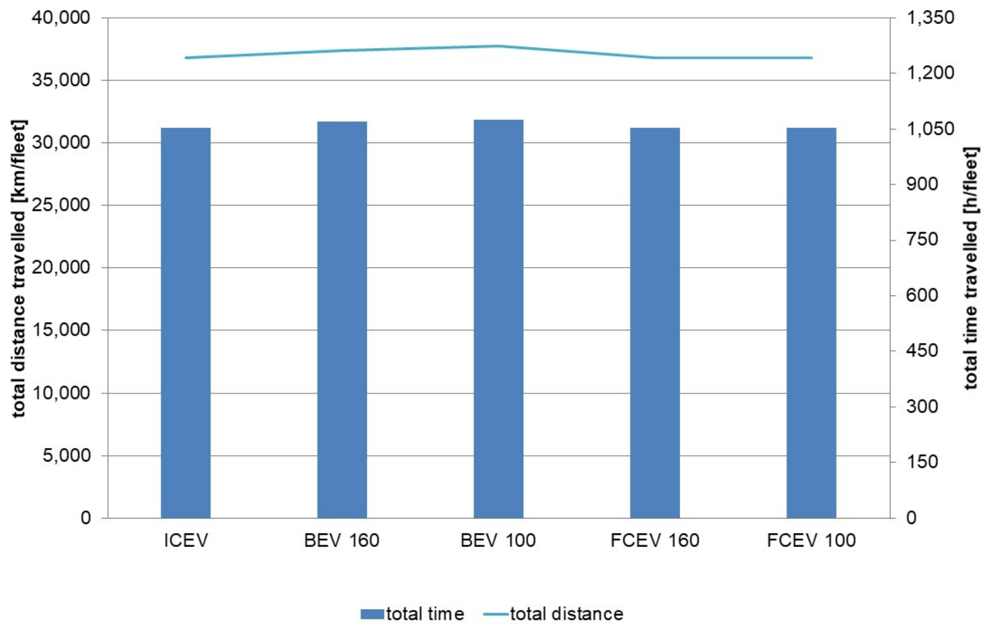

Figure 6 Total Time and Distance Travelled per Fleet Consisting of all Carriers

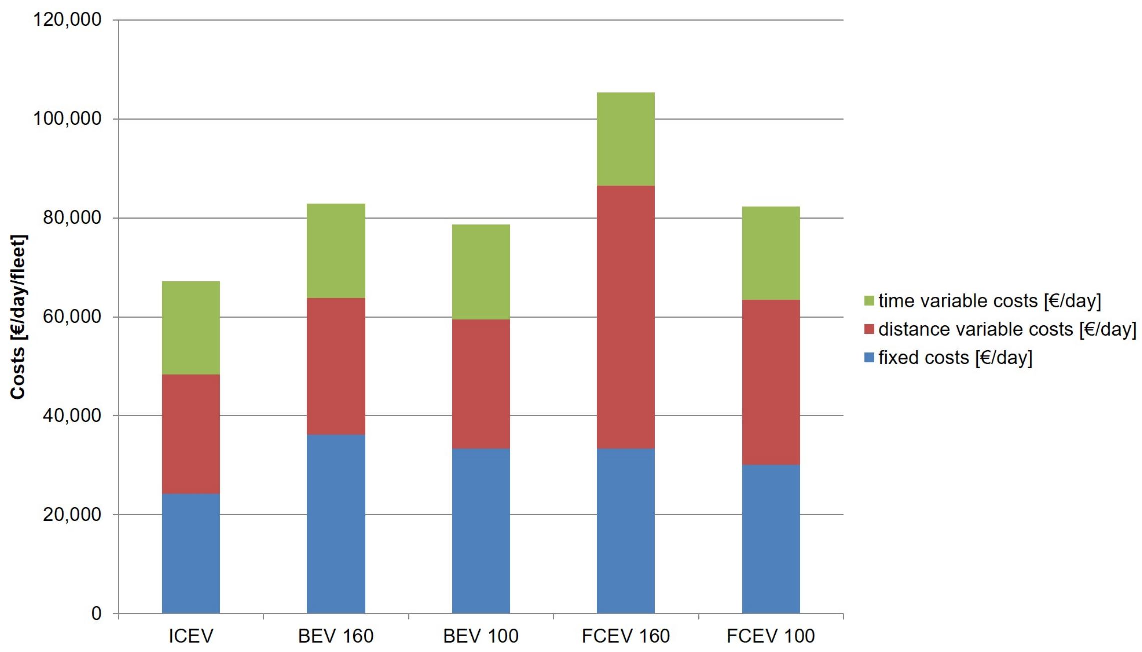

Figure 7 Total Cost of Ownership for the Considered Cases

519 MWh/a with the hydrogen mix from renewable ener-
520 gies. As a result, the FCEV160 case requires 9% more
521 primary energy with the current hydrogen mix com-
pared to the base case while in the FCEV100 case 522
60% more primary energy is needed. The sensitivity 523

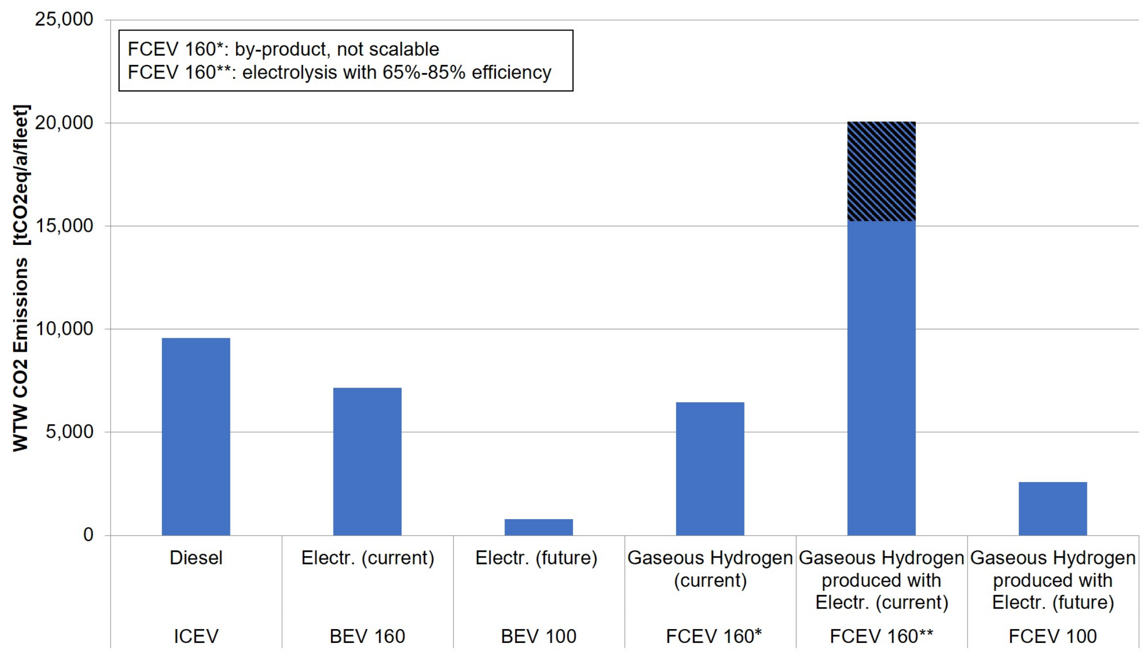

Figure 8 WTW CO2 Emissions of entire Fleet with various Energy Sources

case shows an increase by more than 90% compared to the ICEV base case.

5 Discussion

5.1 Validation of the Parameters

5.1.1 TCO

The investment costs are crucial for the fixed costs. Gnann et al. [7] present with 696,070€ investment costs for a heavy-duty semi trailer higher values for FCEVs than this work (40 tons FCEV: 274,004€ (FCEV160) and 232,904€ (FCEV100)). Daneberg [26], however, calculates investment costs of only 179,996€ (2020) and 126,597€ (2030) for heavy-duty semi trailer tractors (converted at an average exchange rate in 2018: 9.6073NOK = 1€ [49]). After all, these values are all based on individual assumptions, e.g. for fuel cells, tank, battery or glider costs and should therefore be viewed critically. Actual investment costs will be available after the launch of series production of FCEVs. Since fuel consumption for trucks accounts for a large proportion of operating costs, it is important for cost considerations. The fuel consumption for 3.5 - 7.5t heavy FCEVs of 94 - 109kWh/100km, for >12t FCEVs 129-201kWh/100km and for semi trailer tractors 225 - 262kWh/100km from [7] are similar to the assumptions in this study (see Table 1). Gnann et al. [7] calculate TCO for FCEV <12t for 2030 of 30,000€/a at a driving performance of 35,000km/a, whereby no wage costs are included. They assume hydrogen prices from [28], which take into account production costs and distribution costs. For similar mileage, however, this study calculates 42,618€/a for 7.5t FCEV (FCEV100). This includes 9,232€/a wage costs. The annual TCO for 2020 in [27] for Drayage Trucks (equivalent to 26 tons truck class) ranges from 44,670€/a to 51,817€/a and for 2030 from 31,269€/a to 34,843€/a. The costs for fossil hydrogen are 4.57€/kg and 3.73€/kg in 2020 and 2030 respectively and 8.27€/kg and 6.15€/kg for regenerative hydrogen. In this study the costs are 89,753€/a (FCEV160) and 70,652 €/a (FCEV100) for

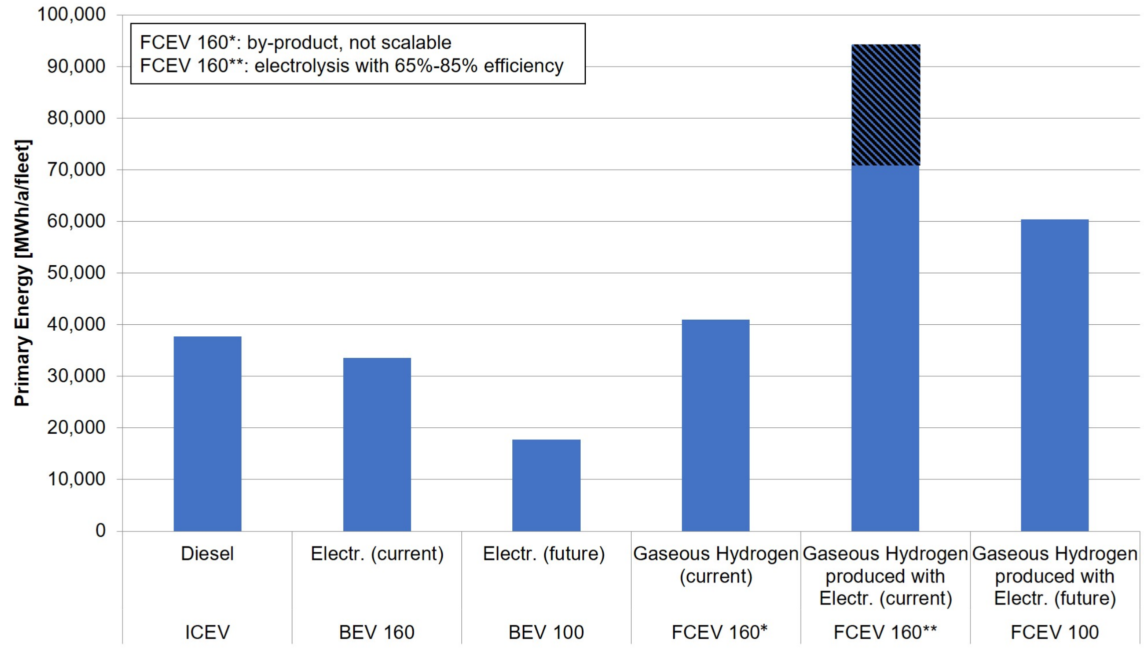

Figure 9 Primary Energy Demand of Entire Fleets with Various Energy Sources

26 tons FCEV. However, to accurately model the effects of more or less tours, this study includes labour costs, which leads to cost differences. Additionally, the assumed hydrogen prices of 13.23 €/kg and 7.13 €/kg contribute to the difference. Besides the different hydrogen prices, a lower consumption of 152.28 kWh/100km for Drayage Trucks in [27] leads to lower operating costs. The assumed hydrogen price in this study includes production costs and investment costs for filling stations, transport and distribution for hydrogen as fuel. Hall and Lutsey [27] give no reference or explanation for the assumption of hydrogen costs. The infrastructure costs are given separately.

5.1.2 WTW - GHG Emissions

Gnann et al. [7] assume GHG emissions (WTW) of 0.324kgCO2eq/kWh for diesel. In this study diesel with 7% biodiesel content is assumed which results in 0.318kgCO2eq/kWh [41]. In [18], the Italian electricity mix with 0.410kgCO2eq/kWh and a fully renewable electricity mix with 0kgCO2eq/kWh are assumed. Gnann et al. [7] assume 0.202kgCO2eq/kWh for 2030. In this study, however, the actual electricity mix from 2019 in Germany is used which results in 0.522kgCO2eq/kWh. In renewable electricity production emissions occur i.a. due to the construction of the respective plants. Therefore we consider 0.057kgCO2eq/kWh for the electricity from 100% renewable sources. Gnann et al. [7] assume 0.306kgCO2eq/kWh (WTW) for hydrogen with production by electrolysis and an average electricity mix for 2030. Lombardi et al. [18] assume three hydrogen paths: Hydrogen production with coal gasification combined with CO2 sequestration, steam reforming of natural gas and electrolysis with 100% renewable energies. This results in 0.200 kgCO2eq/kWh, 0.407kgCO2eq/kWh and 0kgCO2eq/kWh respectively. In this study, however, the current hydrogen mix consists of approx. 50% by-products and 50% steam reforming. This results in 0.258kgCO2eq/kWh. Yazdanie et al. show 0.076 and 0.144kgCO2eq/kWh for

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hydrogen production with electrolysers and electricity from photovoltaic plants and wind [17]. This is 0.110kgCO2eq/kWh with a mix of 50% wind and 50% solar energy, which is comparable to this study with 0.103kgCO2eq/kWh. However, in [17] no emissions due to transport and distribution were considered.

5.1.3 WTW - Primary Energy Demand

In this study, the energy requirement for diesel, at 1.25 kWh/kWhEnergyCarrier, is 3% higher than in [18], which can be explained by the 7% biodiesel content, that requires more primary energy than conventional diesel. According to [18], the energy requirement for the Italian electricity mix is 2.86 kWh/kWhEl, which is 16% higher than the German electricity mix for 2019. This is due to the fact that Germany has been able to increase its share of renewable electricity to 40%. In this study the primary energy requirement for renewable electricity is 1.30kWh/kWhEl (see Table 3), which is 10% higher than in [18] where 100% efficiency and only losses due to electricity distribution are considered for renewable electricity generation. According to Lombardi et al. [18], the energy demand for fossil hydrogen is between 2.18 - 2.76kWh/kWhH2. In this study, however, an energy requirement of 1.64kWh/kWhH2 is considered. The lower energy demand is due to the fact that more than 50% of the hydrogen is produced as a by-product. In the sensitivity case the primary energy factor is with a value of 2.88kWh/kWhH2 even higher than the one presented in lombardi et al.. If renewable electricity is used to produce hydrogen, the primary energy requirement increases to 2.55 kWh/kWhH2 in [18]. In [17], hydrogen production with electrolyzers and electricity from photovoltaic systems and wind requires 1.8 - 2.6 and 1.5 - 2.1 kWh/kWhH2. The energy demand for hydrogen from renewable energies in this study is with 2.42 kWh/kWhH2 in a realistic range, since the energy demand for transport and distribution was considered additionally.

5.2 Evaluation of Results

When considering BEV or FCEV for the total decarbonization of food supply in urban traffic the former is to be prefered. From a cost point of view, FCEVs have higher operating costs due to the price of hydrogen and similarly high investment costs. The advantage of a diesel-equivalent range and refueling time of FCEV is decisive for the decision of the preferred technology, if refueling is necessary to complete the delivery route. However, in the use case at hand the BEVs can reach 56% of all destinations without intermediate charging and 90% with one-time intermediate charging [35]. With additional public fast charging stations in the operation area, all tours can be performed with BEV [6].

With regards to WTW emissions, FCEV have a small advantage over BEV when considering current electricity and hydrogen mixes. However, this hydrogen mix cannot be scaled arbitrarily, since about half of the hydrogen is a by-product from chemical processes, which in all likelihood will not be expanded by an increased demand for hydrogen. Since all of the hydrogen produced today is already absorbed by the market (especially the chemical industry), it can be expected that an increase in consumption by FCEV in the transportation sector would require new generation pathways. Therefore, we have performed the sensitivity analysis where the hydrogen is generated from current electricity. This leads to a high increase in WTW emissions even compared to ICEV. The effect would be similar for hydrogen produced entirely from fossil resources. It is therefore obvious that a positive effect in terms of WTW emissions can only be achieved by hydrogen from renewable sources, as the case FCEV100 shows. However, the achievable savings

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from directly using the renewable electricity in BEV are significantly higher as shown in the case BEV100.

In this study, the investigation of GHG emissions is only related to the energy consumption of the fleets. Thus, the environmental impacts of production, end of life, infrastructure and maintenance are out of scope. For a complete evaluation of the environmental impacts per vehicle fleet, a complete life cycle assessment Life Cycle Assessment (LCA) would be necessary. However, since commercial vehicles have a substantial higher lifetime mileage than passenger cars, the production and recycling emissions account for a smaller proportion of the complete life cycle emissions. In terms of energy consumption, the FCEV160 case is competitive with the ICEV case. However, the primary energy demand of BEV is preferable in all cases for the truck fleet of urban freight transport, since with both, the current electricity mix of Germany and the renewable electricity mix BEV have a smaller primary energy demand than FCEV and ICEV.

6 Conclusion and Outlook

This study examines battery electric and fuel cell electric drive technologies with the objective to investigate their decarbonization effects on urban freight transport. ICEVs operated with diesel provided the base case. The food retailing in Berlin serves as a use case. Considering today's technology and fuel prices, a transition from ICEVs to BEVs would increase costs by 23%. A change to FCEV has more than twice the increase with 57%. In the considered future cases with lower fuel and technology prices BEVs are 17% higher compared to the base case. The transition to FCEVs is with 22% higher costs compared to the base case, still more expensive than BEV but the difference is smaller. When the transition to locally emission free trucks is considered today and today's electricity and hydrogen mixes should be used, FCEVs hold the potential to reduce GHG emissions by 33%. This way, they outperform BEV, which would only achieve a reduction of 25% compared to the base case. However, as previously shown, this effect cannot be scaled up, since these savings are based on the fact that a large part of the hydrogen is a by-product. As soon as more hydrogen has to be produced from today's electricity or fossil fuels, the advantage of the technology becomes smaller and at some point turns into a disadvantage.

When more renewable energy is taken into account, the superiority of BEV is indisputable. If 100% renewables are considered, the savings potential of BEVs is with 92% significantly higher than that of FCEVs with 73%. The analysis of the primary energy demand shows that with Germany's electricity mix of 2019 11% less primary energy would be used when deploying BEVs. For the exclusive use of renewables, this value rises to 53%. FCEVs on the other hand cause a 9% increase in primary energy demand today and 60% more with renewable hydrogen. The range advantage of FCEVs shows to have no importance due to short delivery routes in this urban use case. To make FCEVs more competitive, the price of hydrogen has to decrease, which may result from economies of scale when demand for hydrogen rises. In further studies on the decarbonization of urban freight traffic, a mixed fleet composition of BEVs and FCEVs should be considered. The BEVs' batteries could be designed for short delivery routes, which would result in lower costs due to a smaller battery size. FCEVs can be used to cover the long delivery distances. Prospective research should also investigate FC and BE trucks for rural freight transport. Here, the range advantage of FCEVs could be the game changer for the decarbonization of freight transport. The option of producing hydrogen using PtG plants with surplus regenerative electricity for FCEVs makes sense from an energy utilization point of view. Depending on the configuration and purpose of the PtG plant, the produced hydrogen can

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be converted into electricity or transported to filling stations. With regard to primary energy demand, the question arises as to which of the WTW paths is most efficient for BEVs or for FCEVs. This issue may be the subject of further studies. To better assess the environmental impact of the two technologies, it would be interesting to conduct a full LCA that considers the production, operation and disposal of the vehicle fleets in addition to the WTW emissions. The result of this study is that FCEVs can outperform BEVs in terms of GHG emissions when considering today's hydrogen production and a very small fleet of FCEVs. But in all other considered categories and most importantly when assuming increasing shares of renewable energy, BEVs are the preferred technology choice for urban freight transport. According to our results BEVs are cheaper in total operation cost, reduce the primary energy demand and with rising shares of renewable energies in the grid, they have a higher potential to lower GHG emissions compared to FCEV.

Acronyms

BEV Battery Electric Vehicle. 1–8, 10, 11, 15–17

FC Fuel Cell. 2, 3, 5, 6, 16

FCEV Fuel Cell Electric Vehicle. 1–17

GHG Greenhouse Gas. 1–4, 10, 11, 14, 16, 17

ICEV Internal Combustion Engine Vehicle. 1–7, 10, 11, 13, 15, 16

LCA Life Cycle Assessment. 16, 17

PtG Power To Gas. 2, 8, 16

TCO Total Cost of Ownership. 1–4, 10, 13

TTW Tank To Wheel. 4, 5

VRP Vehicle Routing Problem. 1, 3–5, 10

WTT Well To Tank. 4, 8

WTW Well To Wheel. 1–4, 10, 13–15, 17

Competing interests

The authors declare that they have no competing interests.

Author's contributions

The authors contributed equally to this work.

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