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RESEARCH AND ANALYSIS

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Technoecological analysis of energy carriers for long-haul transportation

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Abstract

Long-haul transportation demand is predicted to increase in the future, resulting in higher carbon dioxide emissions. Different drivetrain technologies, such as hybrid or battery electric vehicles, electrified roads, liquefied natural gas and hydrogen, might offer solutions to this problem. To assess their ecological and economic impact, these concepts were simulated including a weight and cost model to estimate the total cost of ownership. An evolutionary algorithm optimizes each vehicle to find a concept specific optimal solution. A model calculates the minimum investment in infrastructure required to meet the energy demand for each concept. A well-to-wheel analysis takes into account upstream and on-road carbon dioxide emissions, to compare fully electric vehicles with conventional combustion engines. Investment in new infrastructure is the biggest drawback of electrified road concepts, although they offer low CO_2 emissions. The diesel hybrid is the best compromise between carbon reduction and costs.

KEYWORDS

GHG Emissions, industrial ecology, infrastructure, long-haul transportation, vehicle simulation, well to wheel

1 | INTRODUCTION

Climate change is one of the biggest challenges of the 21st century and requires a drastic reduction in greenhouse gas (GHG) emissions to keep the temperature rise to a minimum (IPCC, 2018; Lung & Füssel, 2014). The reduction in carbon dioxide and, thus, stricter regulations in the European Union and the United States present new challenges for the commercial vehicle industry.

1.1 | Motivation

Using predominately fossil fuels, the road freight transport accounts for 75% of all freight-related and 5% of total carbon dioxide emissions (ACEA, 2017; European Environment Agency, 2017). The road transportation and especially the long-haul vehicles (daily distance > 150 km) with a gross weight of more than 15 tons provide a large leverage to decrease the global carbon footprint (International Energy Agency, 2017). However, the steady increase in transportation demand causes a rebound effect. Although the specific energy consumption of commercial vehicles has decreased in the last 30 years (Umweltbundesamt, 2012), the total energy consumption has increased by 20% since 1990 (European Environment Agency, 2017).

To reverse this trend, a variety of technologies have emerged in recent years, primarily driven by the development in the passenger vehicle sector (Zhao, Burke, & Zhu, 2013). Besides the total or partial electrification of the drivetrain using hybrid electric vehicles (HEV), battery electric vehicles (BEVs), or fuel cells electric vehicles (FCEV), substituting diesel with liquefied natural gas (LNG) promises a reduction in GHG emissions. A trend for compensating the low energy density and, thus, the heavy weight of lithium ion batteries compared to fossil fuels, technologies, such as wireless/inductive power transfer (WPT) (Olsson, 2013) or overhead catenary (OC) (Wietschel, 2016; Wietschel et al., 2017), recently became object of research interest. These technologies show different potentials in saving CO_2 emissions but require a high investment in new infrastructure, such as LNG or fast charging stations and road infrastructure.

1.2 | Goal and scope

Today, there are no studies combining detailed vehicle simulations of the above-mentioned technologies regarding their carbon dioxide emissions with required infrastructure costs. This article aims to fill this gap by answering the following research questions:

- How much CO_2 can each vehicle concept decrease?
- What are the system costs including infrastructure, transportation, and carbon tax?
- Which technology provides the best compromise between carbon dioxide reduction and system costs?

A vehicle model yields the energy consumption, as well as the total cost of ownership (TCO) for each vehicle. A well-to-wheel (WtW) analysis assesses the resulting on-road and upstream emissions. This work focuses on CO_2 emissions as the most important anthropogenic GHG (IPCC, 2018). Infrastructure costs can greatly increase the system costs. To assess these costs, the necessary investment in new infrastructure is estimated.

The geographical focus of this study is the European Union. Based on the *United Nation's Agenda 2030* (United Nations, 2015), the time scope is the year 2030. This work presents the results of the given time scope and region as well as a comparison to the GREET model (Burnham, Wang, & Wu, 2006).

2 | STATE OF TECHNOLOGY

This section summarizes the relevant properties of these technologies. The following drivetrain technologies are investigated in this article: (a) diesel (baseline), (b) diesel electric hybrid, (c) LNG electric hybrid, (d) BEV, (e) WPT/OC, and (7) fuel cell. Since the main focus is on drivetrains, synthetic or biofuels are not included.

Commercial vehicles have two major requirements: (a) low TCO and (b) high payload. Long-haul trucks additionally require a sufficient range: A fleet test shows that long-haul trucks drive an average of 400–600 km/day (Fries, 2018; Mährle et al., 2017).

Today 97 % of road transportation is diesel powered; therefore, the diesel engine provides a baseline scenario in comparison to the other technologies (International Energy Agency, 2017).

Due to decreasing battery prices and technological advancements (Fries & Lienkamp, 2016; Hofmann, 2014; Nykvist & Nilsson, 2015), hybrid drivetrains provide a solution to lower the emissions as well as the costs. However, there are only two HEV long-haul trucks on the market today (Kane, 2018a, 2018b) (March 2019).

Figure 1 shows the topology of a parallel hybrid drivetrain. The electrical components add additional weight and cost to the vehicle. Reducing the size of the internal combustion engine (ICE) can compensate for the weight, whereas the reduced fuel costs compensate for the higher purchase price (Fries, Wolff, & Lienkamp, 2017). Depending on the size of the electric motor, several forms of hybrid systems exist, whereas full hybrid systems promise the largest emission savings. If the full hybrid system is equipped with a charging unit, it is called a plug-in hybrid electric vehicle (PHEV) (Hofmann, 2014). PHEVs, thus, require a charging infrastructure and offer the possibility of using renewable energy. Combined with a predictive powertrain control and an optimized operational strategy, the parallel hybrid drivetrain shows a significant reduction in CO_2 emissions (Fries, Kruttschnitt, & Lienkamp, 2017). The hybrid system can be equally applied to diesel and gas engines.

LNG systems use methane (CH_4) for combustion. To be suitable for application in long-haul trucks, the gas needs to be stored at −162°C in its liquid form. This increases the volumetric density of methane and enables the desired ranges for long-haul trucks (International Energy Agency, 2017). The components for storing and providing the gas lead to an increase in the drivetrain's costs (Fries et al., 2017). Methane has lower carbon content than diesel and, thus, lowers carbon dioxide emissions. This property makes methane an object of interest for reducing CO_2 emissions, especially in the United States and China (International Energy Agency, 2017). Nevertheless, methane has two major drawbacks: (a) the efficiency of the ICE is lower than that of a comparable diesel engine and (b) methane slip, which describes the leakage of methane during combustion and refueling (International Energy Agency, 2017). Methane has a significant higher global warming potential than carbon dioxide: 1 g CH_4 is as damaging to the atmosphere as 28 g CO_2 (Pachauri & Mayer, 2015). This drastically reduces the net GHG savings and can even be more harmful than diesel (Camuzeaux, Alvarez, Brooks, Browne, & Sterner, 2015). To be a suitable solution for transportation, a network of refueling stations is required. Especially in Europe, the LNG network is sparse and additional stations are necessary (International Energy Agency, 2017). Compressed natural gas (CNG) is not considered for this study. Because of its lower volumetric energy density compared to LNG, CNG cannot fulfill the requirements in terms of range for long-haul applications (International Energy Agency, 2017).

The trend of BEVs is slowly catching on in the commercial vehicle sector. However, there is currently only one fully electric long-haul prototype truck by Tesla (Tesla, 2019). Electric motors not only offer a higher efficiency than ICE but also entail zero tailpipe emissions (tank-to-wheel [TtW]).

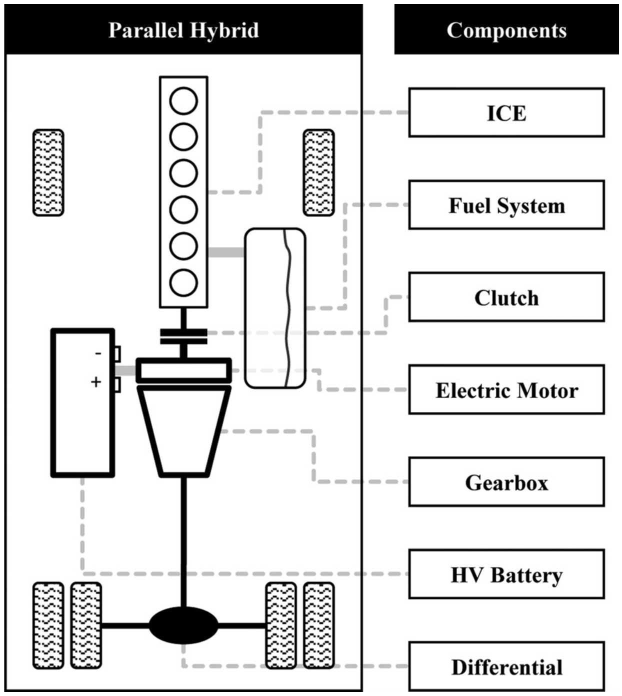

FIGURE 1 Components of a parallel hybrid drivetrain topology

However, in a differentiated analysis, the upstream emissions (well-to-tank [WtT]) that occur during energy production must be taken into account. The major drawback of electric trucks is the battery technology. Current lithium ion batteries have an energy density of less than 200 Wh/kg (Alvarez, 2018; Horlbeck et al., 2014) and, thus, approximately 1% of the energy density of diesel. To achieve the range of 800 km that Tesla claims (Tesla, 2019), the battery mass would have to be between 5–6 tons. The electric powertrain partly compensates for the battery weight but the total payload is still smaller than ICE trucks. In addition to the weight, the costs of lithium ion batteries are high (95–141 €/kWh [Fries et al., 2017]) resulting in a high purchase price.

One approach to reduce the battery size and, thus, costs and weight is an electrified road system that allows charging of the vehicle battery during driving (International Energy Agency, 2017). This can be achieved via conductive energy transfer with overhead catenaries (Wietschel, 2016), similar to electric trains. Another e-road solution is the WPT via induction (Olsson, 2013). Both systems require additional components in the vehicle and on the road to transfer the energy. An electrified road further requires a connection to a high voltage power line. Whereas OC systems achieve a better efficiency ($\eta = 0.96$ [Wietschel, 2016; Wietschel et al., 2017]) of the energy transfer and are a well-known technology, the WPT system can be used by passenger and commercial vehicles. The current Siemens OC system is based on the Scania R450A4 × 2NB tractor (MAbW, 2018). With manufacturer information and a vehicle weight model (Section 3.1), the weight of the OC system is estimated to be 600 kg. The inductive charging technology has higher losses ($\eta = 0.88$ [Navidi, Cao, & Krein, 2016]) that depend on the overlap of the receiving and transmitting coils. The prototype system weight is 591 kg (Karakitsios et al., 2017; Olsson, 2013). Both systems share high infrastructural costs of approximately 2–4 €m/km (den Boer, 2013; Olsson, 2013; Wietschel et al., 2017).

The US company Nikola Motor announced its hydrogen-powered electric truck in 2016 (Nikola Motor Company, 2016) but has not proceeded to field tests yet. FCEV require expensive storage and compressor units. Furthermore, the costs for fuel cells are relatively high, but are expected to drop significantly once large-scale production is achieved (Ekdunge, 2016; International Energy Agency, 2017). The vehicles still require a small battery acting as a buffer storage to compensate for the slow dynamic behavior of the fuel cell. FCEV have zero tailpipe emissions, but the electrolysis requires electric energy to produce hydrogen, which increases the upstream emissions.

3 | METHODOLOGY

To obtain an optimal vehicle for the diesel, LNG, and eRoad vehicles, we combined a parametric vehicle simulation (Section 3.1) with an evolutionary algorithm (Section 3.2). The concept vehicles represent BEV and FCEV from Tesla and Nikola Motors, respectively. An energy demand-based model calculates the infrastructure investment and provides a lower boundary for each technology (Section 3.3). To estimate the GHG reduction potential, a WtW analysis determines the specific CO_2 emissions including the respective upstream emissions (Section 3.4). We assume that emissions from vehicle production only contribute a small share due to the high mileage of long-haul trucks. The presented WtW analysis, thus, neglects these emissions, providing a relative comparison of the technologies.

TABLE 1 Production costs and upstream emissions of energy carriers for 2030

Unit	Costs €/kWh	WtT gCO_2/kWh	Source
Diesel	0.055	37.38	(ProBas; Schmidt et al., 2016)
LNG	0.038	41.10	(ProBas; Schmidt et al., 2016)
Hydrogen	0.219	620.75	(Agora Verkehrswende & Agora Energiewende, 2018; Schmidt et al., 2016)
Electricity	0.10	372	(BDEW Bundesverband der Energie- und Wasserwirtschaft e.V., 2017; Prognos AG, EWI, GWS, 2014)

3.1 | Vehicle model

The base of the analysis is a fully parametric vehicle model for each concept to simulate the energy consumption, and the emissions, respectively, for a given driving cycle. The simulation is built using Matlab/Simulink (Fries, Sinning, Lienkamp, & Höpfner, 2016). All vehicles are simulated with a payload of 19.3 t in accordance with VECTO, which is mandatory for certification in Europe since 2019 (Rexeis et al., 2017).

Generic models for the battery, as well as the fuel cell and scalable engine maps for the ICE and the electric motor are implemented. An additional energy source with different efficiencies models the WPT and OC systems. To assess the different engine and motor characteristics, a scalable gearbox model simulates transmissions from one to 16 gears.

A component-based model calculates the mass of drivetrain components, the curb weight and, thus, the payload for an arbitrary vehicle (Fries, Lehmeyer, & Lienkamp, 2017). Weight functions indicate the specific weight for each component. In addition to the weight functions of Fries et al., the inductive charging system with 591 kg (Olsson, 2013) and the catenary system with 600 kg are included. The fuel cell is calculated with a power density of 0.98 kg/kW (Power Cell Sweden AB, 2017) and an empty tank weight of 17.5 kg/kgH_2 (Artl, 2018).

Key figures for the single components multiplied with the respective parameters and the trading margins result in the total purchase price (Fries et al., 2017). The implemented TCO model consists of four cost parts: (a) kilometer dependent, (b) personnel, (c) time dependent, and (d) overhead costs (Fries et al., 2017). The simulated energy consumption and annual mileage are the inputs for the TCO model. The aim is to give a technical and ecological assessment of the different energy carriers.

The TCO model has different system boundaries than the WtW analysis as it includes the manufacturing costs of the vehicle. For a conventional diesel truck, the purchase price only contributes a small share of the TCO (Wittenbrink, 2014). Lithium ion batteries can double or even triple the purchase price of the vehicle and result in significantly higher TCO. It is, therefore, necessary to include the costs of the electrical components in the vehicle model.

To avoid asymmetries in the results due to uneven taxes, the energy costs are calculated with the respective production costs including transportation (Table 1). Furthermore, it is impossible to forecast the taxes for the year 2030 accurately. Studies by Schmidt, Zittel, Weindorf, and Raksha (2016) and Prognos and EWI (2014) forecast the costs. Collecting over 120,000 km of data, we generated a representative driving cycle that constitutes the input for the vehicle simulation (Fries, Baum, Wittman, & Lienkamp, 2018).

The results of the vehicle simulation are TCO (€/tkm) and transport efficiency (gCO_2/tkm). With regard to the payload, both values account for different component weights such as lithium ion batteries. This allows us to embed the single-vehicle concept in a transportation scenario. The share of long-haul transportation in European road freight transport is 75% (Prognos AG, 2015). Assuming an annual growth rate of 1.5% (European Comission Mobility and Transport, 2017), the long-haul road transportation demand (P_T) is 1.35×10^{12} ton kilometers per year in 2030.

Multiplied by the TCO, we obtain an economic figure for each energy carrier Equation (1). It represents the costs for transportation (C_T) and allows us to compare the economic consequences for European freight carriers for a given vehicle concept. The transportation costs are the first part of the system cost and are comparable to the total turnover of the European freight carriers. High transportation costs can result in a reduction of economic growth or an increase in the price for transportation services.

$$C_T \left[\frac{€}{a}\right] = \text{TCO} \left[\frac{€}{\text{tkm}}\right] P_T \left[\frac{\text{tkm}}{a}\right]. \quad (1)$$

3.2 | Evolutionary algorithm

Different vehicle concepts have different properties and many degrees of freedom regarding their design. To find a vehicle that fulfills the requirements, the vehicle model and an evolutionary algorithm are combined (Fries et al., 2017). With this framework, an optimum vehicle for diesel (PHEV), LNG (PHEV), and OC can be obtained. The technical data of concept trucks by Tesla and Nikola motors represent the vehicle concepts for BEV and FCEV, respectively.

A Matlab implementation (Song, 2011) of the NSGA-II evolutionary algorithm (Coello, Lamont, & van Veldhuizen, 2007) is used to conduct several multiobjective optimizations and find an optimum vehicle for each energy carrier.

An evolutionary algorithm provides two main advantages: (a) its ability to handle nonlinear problems and (b) the handling of contradicting objectives (pareto-optimal solutions). An optimal vehicle concept should have low TCO and at the same time a high transport efficiency. These two objectives can be contradictive if, for example, excessive battery usage achieves low carbon dioxide emissions but shortens the lifespan of the battery. This leads to a replacement of the battery and, thus, a higher TCO. A pareto-optimal solution or paretofront, describes a set of solutions where one single solution outperforms every other solution in at least one objective. Eventually, a decision maker has to choose a solution according to additional measures (Coello et al., 2007).

Besides the low TCO and the good transport efficiency, an optimal vehicle concept must be plausible for use on roads. To assess this issue, the elasticity, or time for acceleration from 60 to 80 km/h ($f_{Elasticity}$) is used as a measure for the driving dynamics. Elasticity is especially important if the driver needs to switch between highways and federal roads and, thus, change the speed limit frequently.

In summary, we obtain the following multiobjective optimization:

$$\min f\left(\vec{x}\right) \rightarrow \min\left(f_{\mathrm{TCO}},\ f_{\eta,\mathrm{Transport}},\ f_{\mathrm{Elasticity}}\right). \tag{2}$$

3.3 | Infrastructure cost model

To know, how much the infrastructure for alternative energy carriers costs, it is necessary to know how many units of infrastructure are required. The model uses the energy demand of each vehicle concept to estimate the number of infrastructure units. Thus, it provides a minimum number of infrastructure units for the respective concept. To provide a best-case scenario, factors, such as spatial resolution (including opportunity charging), are neglected. However, it enables a relative comparison of the infrastructure costs. The amount of infrastructure units is not part of the optimization but rather a result of the respective vehicle energy demand.

This study investigates the following supply stations:

- LNG station,
- Hydrogen gas station,
- 480 V charging station (50 kW),
- Fast-charging station (150 kW),
- Overhead catenary (500 kW [Wietschel et al., 2017]),
- Inductive power transfer (200 kW [Olsson, 2013]).

Because diesel is the predominant fuel for long-haul transportation, a dense network of filling stations exists. It can be assumed that no additional infrastructure is required for the diesel baseline scenario.

Diesel, as well as LNG plug-in hybrid vehicles require a charging infrastructure in addition to the filling stations. Charging with 50 kW for 8 h results in approximately 400 kWh energy. Currently, all available hybrid vehicles have smaller battery sizes (Kane, 2018a, 2018b). Thus, 480 V charging stations can provide sufficient charging times for the PHEV concepts. It is assumed that BEV passenger cars and trucks share the charging infrastructure and both require fast-charging stations (150 kW) to enable acceptable charging times. Since 80% of all trips are shorter than 600 km (Fries, 2018), the indicated range of the Tesla Semi is 800 km is sufficient for most of the daily trips of a European long-haul truck. A 150 kW charging system is able to charge the battery in less than 9 h and, thus, completely during the driver's daily rest periods (Mareev, Becker, & Sauer, 2018). An average utilization of the charging system of 8 h per day (Gnann et al., 2018) and 240 working days per year is assumed.

The electrified road needs a comprehensive coverage to pose a suitable solution for transportation service providers. Both systems are capable of powering the truck and charging the battery at the same time. Due to the lower power transfer, the WPT system requires more coverage to provide the same amount of energy. We assume a coverage of 12% (Wietschel et al., 2017) or 9,500 km of European highway for the OC system. Due to the lower efficiency, the WPT system requires 43% coverage or 34,000 km to provide the same amount of energy. This makes the infrastructure for the OC system 83% cheaper than the WPT system. Table 2 summarizes the costs and daily capacities for the infrastructure units.

The vehicle model provides a specific energy demand $E_{\mathrm{spec.}}$ that is multiplied with the European transport performance, which eventually yields the energy demand. Together with the costs per unit, we obtain the total infrastructure costs C_I (Equation (3)) that form the second part of the system costs. We assume a write-off time of 20 years for the infrastructure components so that the investment distributes evenly.

$$C_I\left[\frac{€}{a}\right] = E_{\mathrm{spec.}}\left[\frac{\mathrm{kWh}}{\mathrm{tkm}}\right] P_T\left[\frac{\mathrm{tkm}}{a}\right] C_{\mathrm{Unit}}\left[\frac{€}{\mathrm{kWh}}\right]. \tag{3}$$

TABLE 2 Costs for infrastructure units

		Costs	Unit	Capacity (MWh/day)	>Source
LNG		1.3	€m	157	(Lee, 2015)
Hydrogen		1.25	€m	120	(Artl, 2018)
480 V Charging		8,000	€	0.2	(Francfort, Bennett, & Richard et al., 2015)
Fast Charging		59,000	€	1.5	(Gnann et al., 2018)
El. road	WPT	3.61*	€m/km	–	(den Boer, 2013; Moultak, Lutsey, & Hall, 2017; Olsson, 2013; Wietschel et al., 2017)
	OC	2.44*	€m/km	–	(den Boer, 2013; Moultak et al., 2017; Olsson, 2013; Wietschel et al., 2017)

*Mean value of the sources.

3.4 | GHG emissions

Besides the costs of a new technology, it is important to assess its ecological benefit, which is measured by the total reduction of CO_2 in tons per year.

To provide a neutral analysis of the different technologies, it is necessary to differentiate the emissions in WtT and TtW emissions. This is particularly important to compare electric and conventional drivetrains. WtT includes all upstream emissions to provide the energy at the filling or charging station such as fuel extraction, refinery, and transportation. The WtT analysis does not include the emissions for the manufacturing of the vehicle and its components, especially the battery. This creates an asymmetry in the study because the costs of battery production are included in the cost model, but the production emissions are excluded. This results from the fact that there is a lot of uncertainty regarding lithium ion batteries. The meta study by Mia Romare (2017) points out that the energy intensity and, thus, emissions of battery production are dependent on the location and electricity mix of the factory. The study also shows that there is no consensus about the carbon impact of battery production: The carbon emissions range from 74–296 $kgCO_2$/kWh. To estimate the potential error, the average of value of 170 $kgCO_2$/kWh (Mia Romare, 2017) is included for comparison. However, the large annual mileage leads to a share of emissions from vehicle use of more than 90%. Additionally, there is a lack of data for the emissions of catenary and inductive charging systems. Thus, emissions from vehicle and infrastructure production for all technologies are omitted in this study. TtW describes the carbon dioxide emitted on the road, measured in gCO_2/tkm, and is equal to the transport efficiency of the vehicle model.

The WtT emissions for the technologies and the electricity mix are shown in Table 1. The upstream emissions of LNG are slightly higher than diesel because of the methane slip during production. Fully electric drivetrains have no TtW emissions. However, they require large amounts of electric energy. The model assumes that an average European mix (2019: 479 gCO_2/kWh) will provide this energy. Furthermore, extrapolated recent data (372 gCO_2/kWh) (European Environment Agency, 2014) is used to meet the 2030 EU climate goals: a reduction of 95% in 2050 compared to 1990 (Bundesministerium für Umwelt, Naturschutz, Bau und Reaktorsicherheit, 2015). The WtT emissions for hydrogen also include the efficiency for hydrogen electrolysis of 70% (Artl, 2018).

The WtW emissions combine the two parts (Equation (4)). To obtain the annual emissions for the considered vehicle concepts, the energy demand and the given transport performance are combined. The conventional diesel-powered vehicle and its WtT emissions provide the baseline scenario. The emissions are subtracted from the examined new concepts to obtain the respective reduction (or increase).

$$\mathrm{WtW}\left[\frac{tCO_2}{a}\right] = (\mathrm{WtT} + \mathrm{TtW})\left[\frac{\mathrm{gCO_2}}{\mathrm{tkm}}\right] P_T \left[\frac{\mathrm{tkm}}{a}\right] 1e^{-6}. \tag{4}$$

3.5 | CO_2 costs

The vehicle model uses production costs for fuels and energy to exclude subsidies for certain energy carriers. This results in lower costs than in reality. To account for this, we summarize the taxes on fuel and electricity in the CO_2 costs C_{CO_2} (Equation (5)) and leave their distribution to the politicians. We can thereby analyze the sensitivity of the system regarding different tax scenarios.

There are different ways to answer the question of the price for GHG emissions and when saving emissions will become a matter of costs rather than goodwill. Power generation is part of the European emission trading system. The price for 1 tCO_2 at the European Energy Exchange amounts to 22 € (March 2019) (European Energy Exchange, 2018). *Kunz*'s comparative study (Kunz, 2013) suggests a price of 25 €/tCO_2 for 2020 and 40 €/tCO_2 for 2030. The mineral oil tax on diesel can be converted to €/tCO_2. The tax in Europe ranges from 127 €/tCO_2 (Bulgaria) to 250 €/tCO_2 (UK) (Campanda GmbH, 2018). Because taxes are an element to support or suppress certain technologies, we assume the same carbon tax for all

TABLE 3 Results for 2030

	Objectives			Costs			Additional information	
	TCO w/o taxes	Transport efficiency	Elasticity	Transportation	Infrastructure	CO_2 Low/ high	Max. Payload	Purchase price
Unit	€/100tkm	gCO_2/tkm	s	€bn.	€bn.	€bn.	t	€
Diesel	5.71	34.94	21.08	77.28	–	1.89 / 11.82	27.38	91,000
Diesel PHEV	5.76	30.83	15.75	77.96	0.01	1.67 / 10.43	27.92	111,000
LNG PHEV	5.70	32.37	13.53	77.10	1.74	1.75 / 10.95	27.97	109,000
Tesla	7.11	15.33	19.3	96.20	4.01	0.83 / 5.19	21.07	281,000
BEV WPT	8.31	16.93	17.4	112.44	61.87	0.92 / 5.73	27.14	129,000
BEV OC	8.41	18.16	17.8	113.76	12.09	0.98 / 6.14	27.12	132,000
FCEV	9.29	25.94	17.0	125.72	0.91	1.89 / 11.82	27.04	135,000

technologies. To assess the wide range of the tax, the model regards two scenarios for 2030: low CO_2 costs of 40 €/tCO_2 and high CO_2 costs of 250 €/tCO_2.

$$C_{CO_2}\left[\frac{€}{a}\right] = \text{WtW}\left[\frac{tCO_2}{a}\right]\text{Price}_{CO_2}\left[\frac{€}{tCO_2}\right]. \quad (5)$$

3.6 | System costs

The system costs C_s consist of three parts: (a) transportation, (b) infrastructure, and (c) CO_2 costs. They combine the costs and benefits of each vehicle concept. Additionally, we place the total costs in relation to the saved emissions. The resulting $C_{s,\text{specific}}$ provides a key figure for comparing different technologies. It relates the total cost per year to the emission reduction per year resulting in €/tCO_2. As a baseline, the costs and emissions for the diesel vehicle are subtracted. The specific system costs enable a comparison to measures outside of the automotive industry such as reforestation or carbon capture and storage.

$$C_S\left[\frac{€}{a}\right] = C_T + C_I + C_{CO_2}, \quad (6)$$

$$C_{s,\text{specific}}\left[\frac{€}{tCO_2}\right] = \frac{C_s}{\text{WtW}} - \frac{C_{S,\text{Diesel}}}{\text{WtW}_{\text{Diesel}}}. \quad (7)$$

4 | RESULTS

The results of the WtW analysis and the cost model are summarized in Table 3. The conventional diesel is the cheapest option and offers the highest payload. The Tesla BEV shows the lowest emissions but also high TCO and smallest maximum payload capacity. The LNG PHEV outperforms the other concept with the lowest TCO but has higher transportation costs than the diesel (PHEV) concept.

To ensure a range of at least 300 km without charging, the resulting vehicle for the OC and WPT system has a battery capacity of 320 kWh, which is 6% higher than the vehicle proposed by Wietschel et al. (2017). The TCO of the OC system is higher than those of the WPT system for two reasons: First, the catenary system leads to a higher drag coefficient (0.6 instead of 0.53 [Fries et al., 2016]) and, thus, higher energy consumption. Second, the higher power transfer of the OC system puts high stress on the battery, resulting in a necessary exchange of the battery during the lifetime of the vehicle and consequently leading to higher maintenance costs. The electrified road systems show the lowest WtW emissions but the highest infrastructure costs.

4.1 | GHG emissions

Figure 2 shows the simulation results of the total CO_2 emissions for the vehicle concepts, as well as the EU target of 30% reduction for new vehicles compared to 2019 vehicles (European Comission Mobility and Transport, 2018). Due to the increasing transportation demand, the emissions of the conventional diesel, as well as the diesel PHEV and LNG PHEV will increase between 2019 and 2030. The electric concepts show a decrease in emission during the examined time span due to improvements in energy generation.

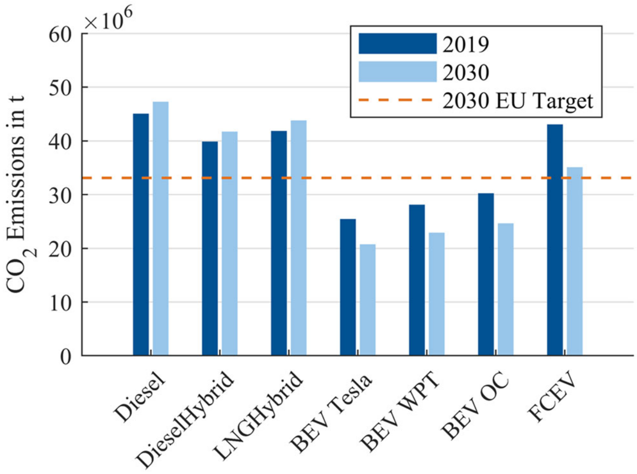

FIGURE 2 Total CO_2 emissions for the year 2019 and 2030 and the EU emission target of 30% reduction for 2030. Underlying data used to create this figure can be found in the Supporting Information S1 available on the Journal's website

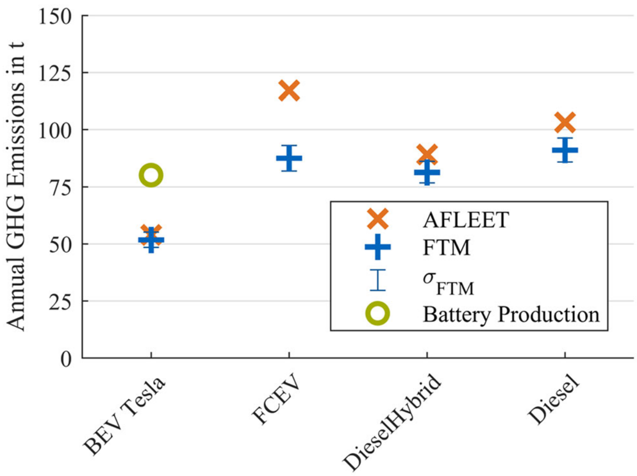

FIGURE 3 Comparison of the absolute, annual GHG emissions with the AFLEET model. Underlying data used to create this figure can be found in the Supporting Information S1 on the Web

The Diesel PHEV has 12% lower emissions than the conventional diesel. The LNG vehicle only saves 7% of GHG emissions due to methane slip. Consequently, combustion engines cannot achieve the EU target in 2030. The BEVs show savings between 49 (WPT) and 57 % (Tesla). The WtW emission of the FCEV is the highest in 2019 with a reduction of 5%. For 2030, the FCEV leads to a reduction of the emissions of 25%.

The CO_2 costs are proportional to the total emissions. In the high CO_2 cost scenario, the diesel concept costs 11.82 billion Euro. The electric concepts cost between 44 and 52% less.

The share of WtT emissions in the total is 12.5% for the diesel and 15% for the diesel PHEV. The upstream emissions account for 19% in the total of the LNG PHEV concept. Converted to annual mileage, the LNG PHEV emits 3.6 tCO_2 more upstream emissions per year than the conventional diesel. Methane slip accounts for 3.6% of the vehicle's WtW emissions or 3.1 tCO_2 equivalent per year.

To verify the results, they are compared to the AFLEET model (Argonne National Lab, 2018). AFLEET is based on the GREET 2.7 by Wang and coworkers and offers life cycle analysis for heavy duty trucks. However, emissions for production of lithium ion batteries are currently not included in AFLEET. Figure 3 shows the total annual emissions for four vehicle concepts supported by AFLEET. LNG PHEV and electrified road systems are currently not supported. The developed model yields 11% lower emissions for the diesel and 9% lower emissions for the diesel PHEV concept. The emissions of the BEV concept are 4% higher in comparison. In the current model, battery production is neglected. If 170 $kgCO_2$/kWh and a lifetime of 6 years (Fries et al., 2016) are assumed, the BEV has the same emissions as the PHEV concept. The high uncertainty in hydrogen upstream emissions (15–1776 gCO_2/kWh [Edwards, Larivé, Rickeard, & Weindorf, 2014]) explains the deviation between the two models for the FCEV (25%). Parameters for upstream emissions and energy/battery costs were varied by ±20% with a Monte-Carlo sensitivity analysis. The standard deviation σ_{FTM} is between 3 and 6%.

4.2 | Infrastructure

The infrastructure costs (cf. Table 3) show a large span. The diesel PHEV is the cheapest vehicle concept regarding the infrastructure costs. To meet the energy demand, approximately 11,000 charging stations with 480 V are required. The Tesla BEV requires 100,000 fast-charging stations to satisfy the energy demand.

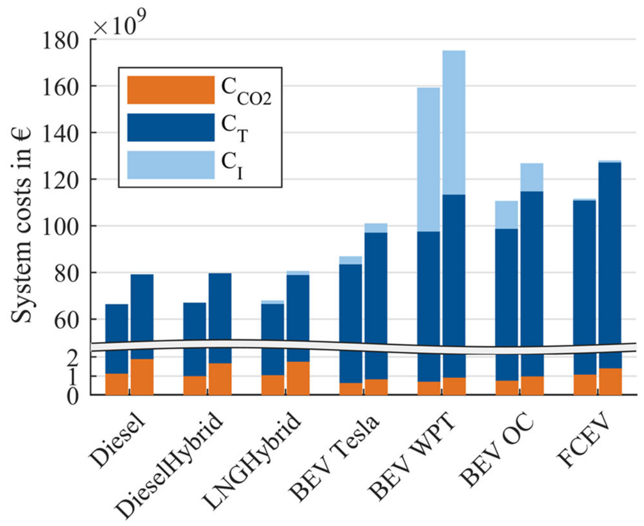

FIGURE 4 Accumulated system costs *CS* for the different vehicle concepts (low CO_2 scenario) for 2019 (left) and 2030 (right). Underlying data used to create this figure can be found in the Supporting Information S1 on the Web

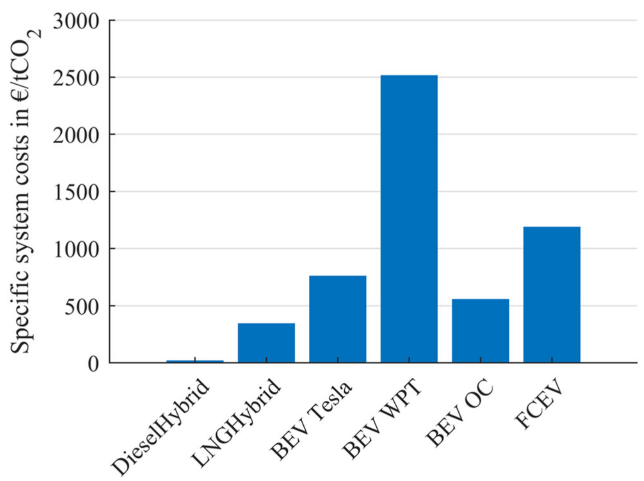

FIGURE 5 Specific system costs for 2030 for the low CO_2 cost scenario. Underlying data used to create this figure can be found in the Supporting Information S1 on the Web

The LNG concepts require approximately 5,000 filling stations, whereas the FCEV concept only needs 2,700 stations because of the higher drivetrain efficiency. This results in 50% lower infrastructure costs.

The electrified road concepts exceed the other infrastructure costs by one to two magnitudes at 62 and 12 billion euro, respectively.

4.3 | System costs

Figure 4 shows the accumulated system costs in Euro (Equation (6)) for the examined vehicles for the years 2019 (left column) and 2030 (right column). In this study, the entire infrastructure will be available from 2019. However, the costs are written off over a period of 11 years, so that they are distributed evenly between 2019 and 2030.

The three ICE vehicles have the lowest system costs with a deviation of 1.10 (2019) and 1.05 (2030) billion €, respectively. The system costs for the electrified road system are the highest and exceed the diesel concept by 220 (WPT) and 160% (OC).

For 2030, the CO_2 costs account for 2–3% of the system costs of the ICE/PHEV concepts. The share of the CO_2 costs for the BEV is less than 1 and 1.3% for the FCEV concept.

The infrastructure costs of the WPT systems constitute to approximately one third of the concept costs. The fast-charging infrastructure for the Tesla concept accounts for 4% of the costs, whereas the 480 V charging infrastructure for the two PHEV concepts accounts for less than 0.1%. The LNG filling stations constitute to 2.4% of the LNG PHEV system costs.

Figure 5 shows the specific system costs (Equation (7)) for 2030. The diesel concept is used as reference. The diesel PHEV concept shows the lowest specific system costs at 22.5 €/tCO_2, whereas the FCEV concept has the highest costs at 3,950 €/tCO_2.

While the effect of the higher CO_2 costs is low (1–2%) for the fully electric vehicle concepts, the share for the PHEV concepts is relatively high (15 and 24%). However, the high CO_2 cost scenario does not change the order of the results.

5 | DISCUSSION

There is no fully electric solution that outperforms fossil fuels regarding the system costs. Although the CO_2 costs are higher for the diesel and LNG systems, the electric concepts are not economically attractive. The fully electric concepts offer CO_2 savings of up to 60%. To make the electric concepts cheaper than the fossil fuels, CO_2 costs need to be several magnitudes larger. There is no study predicting such high CO_2 costs.

Although batteries have become cheaper and lighter (Fries et al., 2017), the technology cannot fulfills the requirements on range and payload for long-haul trucks. Payloads reduced by 22% lead to very high TCO. The higher efficiency of the BEV drivetrain cannot compensate this disadvantage. If a doubled energy density (300 Wh/kg) and a 50% cost reduction (50 €/kWh) is assumed, the Tesla truck is still not economically competitive compared to a diesel truck. The breakeven production price of diesel is 1.4–1.5 €/l or 300% more than today. For a constant payload of 14 tons and current battery data, the breakeven price of diesel is between 1.3 and 1.5 €/l. This shows that without high CO_2 taxation, even for very optimistic assumptions, a BEV will not be competitive for long-haul transportation. A variation of the CO_2 price shows that, if the maximum payload is used, the breakeven for the BEV is at 820 €/tCO_2. For a fixed payload of 14 t it is at 200 €/tCO_2. The number of fast-charging stations required to satisfy the energy demand is much lower than the number of vehicles in Europe (Shell Deutschland Oil GmbH, 2016). It is very likely that the investment in charging infrastructure will be higher than the presented values, if spatial resolution and opportunity charging is included.

The electric road systems show the highest potential in emission savings and provide a high payload. It is, however, unlikely that a coverage of 12% or even 43% throughout Europe can be achieved by 2030 or later. The high infrastructure costs restrict the electrified concepts to specific, isolated solutions such as harbors. Both concepts have a higher power transfer than conventional fast-charging and, thus, higher stress on the battery, which reduces its lifetime. The WPT vehicle requires one exchange while the OC vehicle requires two exchanges of the battery during its use phase of 6 years. This results in higher TCO of the OC system. Furthermore, the costs of the pantograph (10,000 €) are estimated to be higher than the IPT system (7,800 €) (den Boer, 2013). The vehicle model shows that both concepts are most sensitive to the battery life regarding the TCO. If the battery life is completely neglected, both systems become economically competitive to the diesel. The resulting TCOs of the WPT vehicle are 5.88 and 5.95 €/tkm for the OC, respectively, and, thus, approximately 4–5% higher than the diesel.

The results show that the FCEV concept is neither competitive regarding emissions nor costs. This is due to the high hydrogen price, which is four times higher than diesel. Additionally, the upstream emissions of the hydrogen production are 60% higher than the production of electricity alone. Finally, even under the assumptions that the EU reaches the desired climate goals for 2030, the production of hydrogen in Europe will lead to increased GHG emissions. The FCEV concept can only become competitive, if the hydrogen is produced with a higher share of renewable and emission-free energy.

The LNG PHEV has relatively low system costs although it requires investment in new infrastructure. The higher GHG emissions lead to higher specific system costs compared to the diesel PHEV. A sufficient network of LNG charging stations by 2030 is, however, unlikely: The IEA currently counts 61 stations (International Energy Agency, 2017) in Europe, and projects, like the *Blue Corridor* project, have built 12 stations in the last 5 years (Lebrato, 2015). Even with the assumed market share of 100% LNG trucks, the emission savings are comparable to those of the diesel PHEV concept.

Considering the technology readiness and the required infrastructure, the diesel PHEV is the only completely viable solution until 2030, although it has the lowest GHG savings. Furthermore, the infrastructure of the diesel PHEV can provide a transition scenario for electric mobility, because the charging stations can be shared among all concepts and even passenger cars. However, other options might be viable for certain corridors such as highly frequented or urban highways.

The infrastructure model is energy demand based. It does not account for the geographical placement of the infrastructure units and it is likely that additional units (such as opportunity charging) are required to provide a practical coverage. Additionally, the resulting emission savings provide a best-case scenario. The results assume that the long-haul transportation uses a single vehicle concept by 2030 to reap the maximum possible GHG savings. Thus, the results presented in this article represent a lower boundary for the emissions and consequently the system costs.

Although the presented model does not include the emissions from vehicle production, it shows good agreement with results of the AFLEET model. The high annual mileage of long-haul trucks decreases the share of production of the total emissions.

As shown in this article, the results are very sensitive to the payload. For further studies, the vehicle fleet should be broken down more finely to better reflect the real fleet. Different technologies might be better suited for different payloads.

6 | CONCLUSION

Emerging technologies provide different solutions for reducing the carbon footprint in the long-haul transportation sector. In this study, vehicle simulations were combined with a WtW analysis and infrastructure cost models to assess the ecological and economic impact of six drivetrain technologies. Although this analysis neglects the emissions from vehicle production, it shows good agreement with the GREET model. However, to provide a complete analysis, a life-cycle analysis should be included in future works. There is also a lack of data regarding the emissions from the construction of infrastructure such as electrified road systems. More research is necessary to close this gap and enables the life-cycle analysis of the whole transportation system.

The BEV concept shows the lowest GHG emissions, whereas the diesel PHEV concept has the lowest system costs. With the current technology, BEV cannot fulfill requirement on costs and range for long-haul transportation. A BEV long-haul truck requires lighter and less expensive batteries to become competitive. In addition, with the current technology, electric trucks would lead to an increase in traffic because more vehicles would be necessary to transport the same amount of goods.

The WPT and OC system combine high payload with high drivetrain efficiency but require large infrastructure investment. With improving battery technology, the exchange of the batteries could become obsolete resulting in competitive TCO compared to fossil fuels. The remaining difference of 4–5% could be leveled with taxes and subsidies, making the concept attractive for haulers. In this scenario, the specific system costs of the OC system are 40% lower than the WPT. In conclusion, the OC system should be preferred for long-haul transportation. However, as Márquez-Fernández, Gabriel, Lars, and Mats (2017) highlight, it might be necessary to share infrastructure. They conclude that the WPT system should be preferred if mixed traffic is considered. For both systems, it is necessary to optimize the battery life and charging strategies. The possibility to relate the battery size of the electrified road vehicles to the covered infrastructure would further optimize the vehicles. Additionally, a comparison of the infrastructure maintenance costs should be included in future studies, as it might create asymmetry in the current comparison.

The hybridization of conventional diesel engines provides a viable compromise until 2030. However, more research is needed to optimize ICE and develop better batteries, as well as alternative fuels to enable emission-free transportation by 2030 and beyond.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section at the end of the article.

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