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Review article

Market diffusion of alternative fuels and powertrains in heavy-duty vehicles: A literature review

Philipp Kluschke [a,*], Till Gnann [a], Patrick Plötz [a], Martin Wietschel [a,b]

[a] Fraunhofer Institute for Systems and Innovation Research ISI, Breslauer Strasse 48, 76139 Karlsruhe, Germany
[b] Institute for Industrial Production (IIP), Chair of Energy Economics, Karlsruhe Institute of Technology (KIT), Hertzstrasse 16, 76187 Karlsruhe, Germany

HIGHLIGHTS

- Heavy duty vehicles (HDV) will become a relevant player in the electricity market.
- Alternative fuels and powertrains (AFP) expected on low scale following current regulations.
- High uncertainty regarding the emergence of a superior AFP technology for HDV.

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ABSTRACT

With about 22%, the transport sector is one of the largest global emitters of the greenhouse gas CO_2. Long-distance road freight transport accounts for a large and rising share within this sector. For this reason, in February 2019, the European Union agreed to introduce CO_2 emission standards following Canada, China, Japan and the United States. One way to reduce CO_2 emissions from long-distance road freight transport is to use alternative powertrains in trucks — especially heavy-duty vehicles (HDV) because of their high mileage, weight and fuel consumption. Multiple alternative fuels and powertrains (AFPs) have been proposed as potential options to lower CO_2 emissions. However, the current research does not paint a clear picture of the path towards decarbonizing transport that uses AFPs in HDVs. The aim of this literature review is to understand the current state of research on the market diffusion of HDVs with alternative powertrains. We present a summary of market diffusion studies of AFPs in HDVs, including their methods, main findings and policy recommendations. We compare and synthesize the results of these studies to identify strengths and weaknesses in the field, and to propose further options to improve AFP HDV market diffusion modelling. All the studies expect AFPs on a small scale in their reference scenarios under current regulations. In climate protection scenarios, however, AFPs dominate the market, indicating their positive effect on CO_2 reduction. There is a high degree of uncertainty regarding the emergence of a superior AFP technology for HDVs. The authors of this review recommend more research into policy measures, and that infrastructure development and energy supply should be included in order to obtain a holistic understanding of modelling AFP market diffusion for HDVs.

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* Corresponding author.
E-mail address: philipp.kluschke@isi.fraunhofer.de (P. Kluschke).

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Abbreviations

AFP	Alternative Fuels and Powertrains
BEV	Battery Electric Vehicle
BIO	Biofuels
CAT	Catenary electric vehicle
CNG	Compressed Natural Gas
eMET	e-Methane
eSYN	e-Synfuel
EU	European Union
GHG	Greenhouse Gas Emissions
HDV	Heavy Duty Vehicle
HYB	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
FCEV	Fuel Cell Electric Vehicle
LDV	Light Duty Vehicle
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
TCO	Total Cost of Ownership
tkm	Ton kilometres

1. Introduction

The World Climate Report from 2014 describes one of the biggest challenges of the 21st century: climate change. A significant reduction in greenhouse gas (GHG) emissions is required (IPCC, 2013) in order to keep its impacts on humans and the environment as low as possible. Many countries worldwide have defined both joint and individual targets to reduce the emissions of a major GHG: CO_2 (United Nations, 1998; Wietschel et al., 2018; BMUB, 2016; EC, 2015).

The transport sector is a key emitter of CO_2, accounting for around 22% of the total global energy-related CO_2 emissions in 2015. Within this sector, road freight transport represents a very large share of approximately 40%, which will continue to increase (IEA, 2017).

1.1. Carbon footprint of heavy-duty vehicles

According to (IEA, 2017), the global stock of trucks consists mainly of light-duty vehicles ($<$3.5t, approx. 70% of the fleet) and only a small proportion of heavy-duty vehicles (HDV $>$12t, less than 15% of the fleet). However, HDVs have a higher share in total truck mileage as they are mainly used for long-distance transport. Furthermore, their higher specific energy consumption per vehicle means that HDVs account for up to 30% of the CO_2 emissions of the truck stock (Muncrief and Sharpe, 2015). Fig. 1 shows the CO_2 emissions in different world regions in million tons as well as additional assumptions about annual mileages and CO_2 emissions per kilometre based on (IEA, 2017).

In February 2019, the European Union (EU) therefore agreed to introduce CO_2 emission standards for heavy-duty vehicles of −30% until 2030 following Canada, China, India, Japan and the United States (European Commission, 2019). As shown in Fig. 2, the EU is the last major market to install such mandatory regulations. VECTO (Vehicle Energy Consumption Calculation Tool) is applied throughout the EU to determine, monitor and report the CO_2 emissions and fuel consumption of each manufacturer.[1] In order to reach the ambitious EU targets, a significant reduction of CO_2 emissions in the HDV sector is necessary. According to (Eiband and Hohaus, 2018), the CO_2 reduction potential of current diesel technologies is estimated at less than 15%.[2] Hence, the European regulatory objective incentivizes the use of alternative fuels and powertrains (AFP) for HDVs. AFPs therefore represent an important alternative to diesel-fuelled HDVs, which make up nearly 100% of the stock at present (Muncrief and Sharpe, 2015).

Extensive research has been done on AFPs in passenger vehicles since the beginning of this century because of their comparatively low CO_2 abatement costs (Hein et al., 2007). However, the use of AFPs in passenger or light-duty-vehicles (LDVs) differs significantly from their use in HDVs in terms of technology requirements, total-cost-of-ownership (TCO) and infrastructure use. Research on AFPs in HDVs is currently an emerging field in the mobility sector, because it offers lower abatement costs than introducing AFPs in the shipping or aviation sectors (Hein et al., 2007). However, the research discusses various AFPs without painting a clear picture of their market diffusion or contribution to CO_2 reductions. The authors identified two groups of technologies to decarbonize HDVs based on den Boer et al. (2013). The first group "alternative fuels" comprises six different types of fuel, while the second group contains four electrified powertrains.

1.2. Alternative fuels and powertrains

Alternative fuels minimize the specific CO_2 emissions of ICEs and are based on fossil fuels or renewables. Liquefied petroleum gas (LPG) contains mainly propane and butane, which are liquefied at comparatively low pressures of around 5 to 10 bar. Liquefied natural gas (LNG) has a similar state of aggregation, but contains mainly methane and is liquefied by cooling the gas down to −160 °C. In contrast, compressed natural gas (CNG) is stored as a gas in the tank at 200 bar. Renewable fuels include e-methane (eMET, gaseous, 200 bar) and e-synfuels (eSYN, liquid

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[1] Each regulated market regulatory scheme is different and uses a different standard type measurement for HDVs. For example, the USA applies both fuel consumption and CO_2 emission standards (e.g. the Federal Test Procedure Transient tool), China has a fuel consumption regulation, and the EU focusses on CO_2 emissions (using the VECTO tool).

[2] The engine optimization potentials considered for heavy-duty vehicles are heat recovery systems (potential between 1.5% and 2.5%), reduction of friction losses (up to 4%), improvement of auxiliary equipment (up to 5%), exhaust gas aftertreatment (up to 3%), and downspeeding (up to 0.8%).

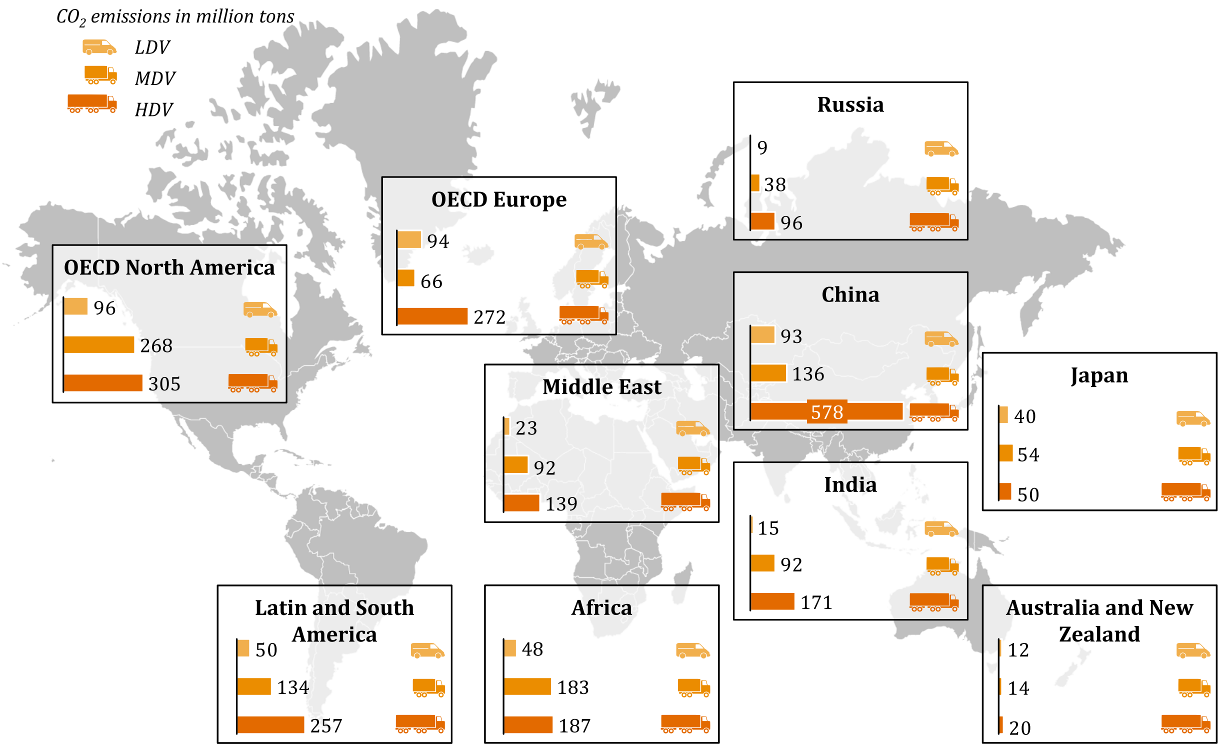


Fig. 1. Global well-to-wheel CO_2 emissions of road freight vehicles in 2015 based on IEA (2017).

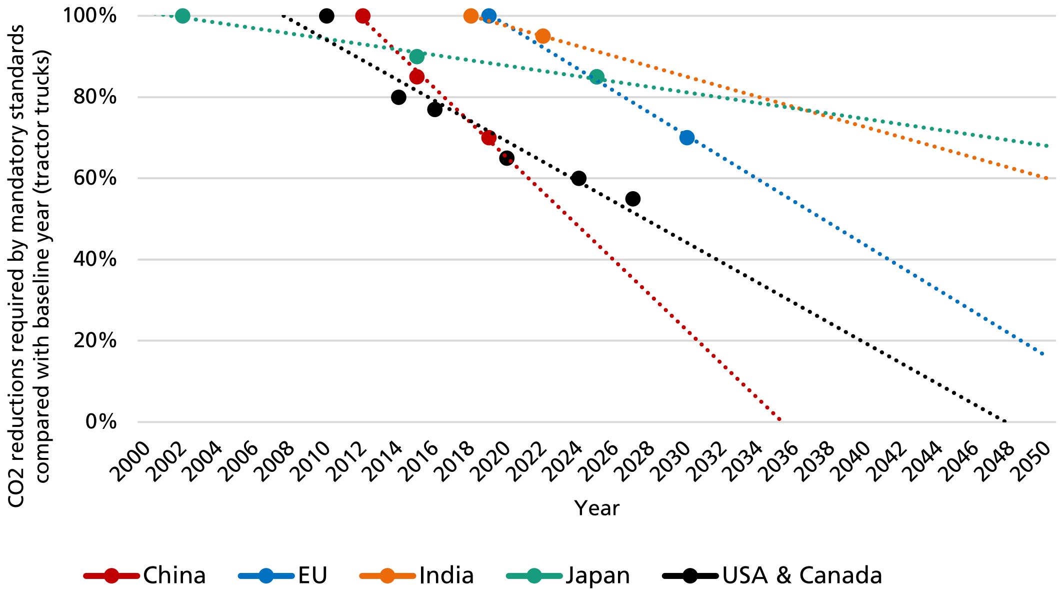


Fig. 2. Heavy-duty vehicle CO_2 standards (coloured dots) for different world regions including Canada, China, EU, India, Japan and USA and linear trend line until 2050 based on current policies (dotted lines), illustration based on Rodriguez (2019). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

at atmospheric pressure), which are produced using electricity in power-to-gas and power-to-liquid applications. Biofuels (BIO) are liquid or gaseous fuels produced from biomass such as plant or animal waste.

Electrified powertrains use electric motors for propulsion. Battery-electric vehicles (BEV) store the electric energy in on-board battery packs, which can be recharged conductively or inductively at charging stations. Catenary electric vehicles (CAT), also called “e-roads”, use a similar technology but rely on overhead lines providing continuous power and have a second powertrain (e.g. an ICE or a larger battery like BEVs) to cover small distances without overhead lines. Hybrid electric vehicles (HYB) also operate with two powertrains, and are classified as an interim stage between diesel-powered ICE and BEV technology. There are two types of HYB technology: with or without on-board charging equipment. Without the equipment, the HYB charges only by recuperating energy while driving. Fuel cell electric vehicles (FCEV) use on-board hydrogen storage to generate electricity within a fuel cell. The hydrogen is usually stored at 350 or 700 bar.

1.3. Research on alternative fuels and powertrains

In general, the research on AFPs for HDVs currently comprises two types of studies. The first category focusses on vehicle design (Kast et al., 2017; Gangloff et al., 2017; Macauley et al., 2016; Ridjan et al., 2013) and the economic viability (Connolly, 2017; Zhao et al., 2013; Gnann et al., 2017; Sen et al., 2017; Mareev et al., 2018; Jordbakke et al., 2018) of HDVs with AFPs. This literature review examines the second category, which deals with the diffusion of AFPs in the HDV market.

As the market diffusion of AFPs in HDVs is a potential lever for large CO_2 reductions and as the current research does not point to an unambiguous path towards HDV decarbonization, an overview of the existing research findings is beneficial for future research. The authors provide such an overview of AFP market diffusion studies for HDVs, synthesize the state of research and derive recommendations for future research. To the best of our knowledge, this paper is the first to summarize the approaches and key findings of research on AFP market diffusion in the HDV sector. This paper differs from others concerning the transport segment (HDVs), analysis criteria (research questions, design of market diffusion models and their output) and technologies (AFPs) examined.

1.4. Objective and research questions

The aim of this review is to present the current state of research on the market diffusion of HDVs with alternative fuels and powertrains to decarbonize global heavy-duty traffic. This work presents a summary of market diffusion studies of AFPs for HDVs, their methods, main findings and recommendations. The authors focus on research questions, modelling design and market diffusion outcomes when generalizing the findings from current research.

The authors compare and synthesize the results of these studies to address four research questions. First, the authors want to understand the impact of AFPs on the future HDV fleet and therefore analyse the market diffusion scenarios (output) of the reviewed studies and identify existing models and results regarding the market diffusion of alternative fuels and powertrains in HDVs. Second, the authors are interested in a better understanding of the modelling results and therefore examine the model design. Transparent model designs support us in interpreting the market diffusion outcomes. Third, the authors identify those AFP technologies that are considered when developing future scenarios in the current literature. Differentiating the AFPs considered in the studies gives insights into the convergence or divergence of particular AFP technologies in the HDV segment. Finally, the authors want to understand what influences market diffusion (drivers and barriers) in the HDV segment. Obtaining an overview of the levers for AFPs in HDVs helps us to understand how to promote AFPs and reduce CO_2 emissions in the transport sector.

The structure of this paper is as follows: The authors describe the data sources, data collection and procedure used for the literature review, as well as briefly reviewing key studies in Section 2. Section 3 contains the findings from the specific models, the market diffusion results for AFPs in HDVs (Section 3.1), and the synthesis regarding strengths (Section 3.2) and weaknesses (Section 3.3). A discussion of the literature is presented in Section 4 and the authors close with conclusions and suggestions for further research in Section 5.

2. Material and method

This section describes how the authors selected the studies, data sources and data collection for this review. The authors present the review method and an overview of all the studies analysed.

2.1. Data collection

In order to identify suitable research on the topic of AFP market diffusion in HDVs, the authors conducted a comprehensive search of publications in online libraries: namely Ebsco, Google Scholar and Science Direct.

The authors used five dimensions to select the studies: Definition of HDV, scientific level, time horizon, search terms and languages. First, "heavy-duty vehicles" are our focus. HDVs are not uniformly defined by weight; there are different regional categorizations. Some countries, such as the US, define HDVs as single vehicles ('vehicles' or 'trucks'). Others separate HDVs into vehicles and vehicles with trailers ('trailers & semitrailers' or 'tractors'), e.g. the EU or China. Due to these heterogeneous HDV definitions, the authors based the definition of HDVs for this review on the international truck categories shown in Table 1: The US vehicle category 8, the EU vehicle category N3 and (semi-)trailer category Q4, as well as Chinese trucks with a weight above 16 tons and a tractor weight above 18 tons were considered. Second, the authors limited the studies to those in peer-reviewed journal papers and studies of renowned scientific institutions to ensure quality standards. Third, the authors focussed on literature from 2011 onwards to provide current research insights and ensure the comparison of up-to-date research. Fourth, the authors selected literature using combinations of the following search sets M_1 to M_3 in both English and German (no results were found using the French and Spanish equivalents):

(a) M_1("trucks" $\vee$ "heavy-duty" $\vee$ "long-haul") $\cap$
(b) M_2("alternative fuels" $\vee$ "alternative powertrains" $\vee$ "decarbonization" $\vee$ "electrification" $\vee$"electric road") $\cap$
(c) M_3("market diffusion" $\vee$ "market penetration")

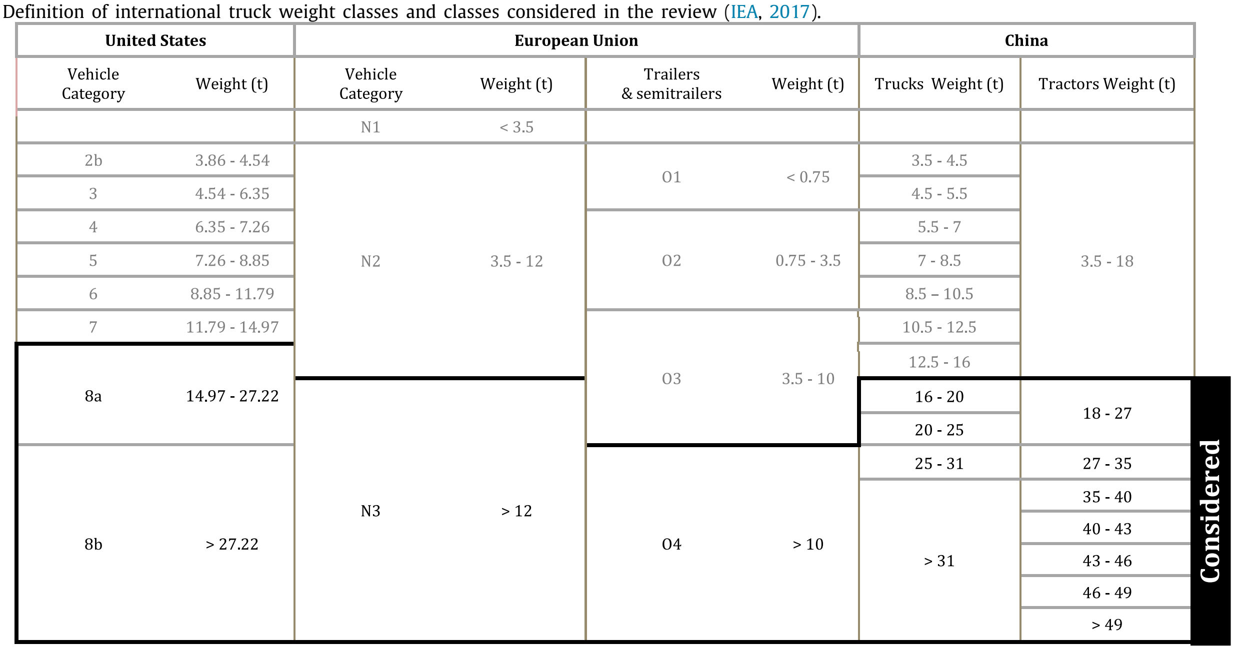
The resulting literature set contains 46 studies without further filtering. These studies were then content crosschecked to narrow them down to the most relevant studies. The authors use three fulfilment criteria for the content crosscheck: The studies need to focus on the relevant HDV sizes (cf. chapter 'Data collection'), contain market diffusion models and incorporate quantitative data regarding the market penetration of AFPs. This resulted in 19 studies for the review, comprising eight peer-reviewed journal publications, two PhD theses and nine scientific reports (see Table 2). The relatively low number of relevant studies already indicates the early research stage of this topic and the lack of research in some developed countries (e.g. France and Japan) and in most developing markets such as Africa, India, the Middle East and Latin America.

2.2. Review method

This section presents the method used to analyse the data output of the previous section. As this review focusses on the diffusion of a particular innovation (AFPs) in socio-economic systems (HDV stock), the analysis criteria are set up along three categories based on the general modelling of social systems (Luhmann and Knodt, 1995; Karnowski, 2017): Environmental parameters (I), input and throughput parameters (II) and output parameters (III).

In order to apply this approach to our work, the authors renamed the category 'environment' 'model objective' and consolidated the input and throughput parameters as 'model design' (see Fig. 3).

Table 1
Definition of international truck weight classes and classes considered in the review (IEA, 2017).



United States		European Union				China	
Vehicle Category	Weight (t)	Vehicle Category	Weight (t)	Trailers & semitrailers	Weight (t)	Trucks Weight (t)	Tractors Weight (t)
		N1	< 3.5				
2b	3.86 - 4.54	N2	3.5 - 12	O1	< 0.75	3.5 - 4.5	3.5 - 18
3	4.54 - 6.35					4.5 - 5.5	
4	6.35 - 7.26			O2	0.75 - 3.5	5.5 - 7	
5	7.26 - 8.85					7 - 8.5	
6	8.85 - 11.79					8.5 – 10.5	
7	11.79 - 14.97			O3	3.5 - 10	10.5 - 12.5	
8a	14.97 - 27.22					12.5 - 16	
		N3	> 12			16 - 20	18 - 27
						20 - 25	
8b	> 27.22			O4	> 10	25 - 31	27 - 35
						> 31	35 - 40
							40 - 43
							43 - 46
							46 - 49
							> 49

Considered

Table 2
Data collected as input for the literature review consisting of eight peer-reviewed journal publications, two PhD theses and nine scientific reports.

Author	Focus region	Title	Observation period	Type of publication
Ambel (2017)	EU28	Roadmap to climate-friendly land freight and buses in Europe	2020 to 2050	Study
Askin et al. (2015)	USA	The heavy-duty vehicle future in the US: A parametric analysis of technology and policy trade-offs	2030 to 2050	Peer-reviewed paper
Bahn et al. (2013)	Canada	Electrification of the Canadian road transportation sector: A 2050 outlook with TIMES-Canada	2020 to 2050	Peer-reviewed paper
Bründlinger et al. (2018)	Germany	Pilot Study Integrated Energy Turnaround: Impulses for the design of the energy system until 2050	2030 to 2050	Study
Çabukoglu et al. (2018)	Switzerland	Battery electric propulsion: An option for heavy-duty vehicles? Results from a Swiss case study	none (only potential)	Peer-reviewed paper
Capros et al. (2016)	EU-28	EU Reference Scenario 2016: Energy, transport and GHG emissions trends to 2050	2030 to 2050	Study
Gambhir et al. (2015)	China	Reducing China's road transport sector CO_2 emissions to 2050: Technologies, costs and decomposition analysis	2050	Peer-reviewed paper
Gerbert et al. (2018)	Germany	Climate paths for Germany	2020 to 2050	Study
Kasten et al. (2016)	Germany	Development of a technical strategy for the energy supply of transport up to the year 2050	2020 to 2050	Study
Liimatainen et al. (2019)	Finland & Switzerland	The potential of electric trucks — An international commodity-level analysis	none (only potential)	Peer-reviewed paper
Mai et al. (2018)	USA	Electrification Futures Study: Scenarios of Electric Technology Adoption and Power Consumption for the United States	2020 to 2050	Study
Mulholl et al. (2018)	Global	The long haul towards decarbonizing road freight — A global assessment to 2050	2030 to 2050	Peer-reviewed paper
Naceur et al. (2017)	Global	Energy Technology Perspectives: Catalysing Energy Technology Transformations	2060	Study
Özdemir (2011)	Germany	The Future Role of Alternative Powertrains and Fuels in the German Transport Sector	2020 to 2030	PhD-Thesis
Plötz et al. (2019)	EU-28	Impact of Electric Trucks on the European Electricity System and CO_2 Emissions	2020 to 2040	Peer-reviewed paper
Repenning et al. (2015)	Germany	Climate protection scenario 2050	2020 to 2050	Study
Seitz (2015)	Germany	Diffusion innovativer Antriebstechnologien zur CO_2-Reduktion von Nutzfahrzeugen	2020 to 2035	PhD-Thesis
Siegemund et al. (2017)	Germany	The potential of electricity-based fuels for low-emission transport in the EU	2020 to 2050	Study
Talebian et al. (2018)	Canada	Electrification of road freight transport: Policy implications in British Columbia	2040	Peer-reviewed paper

In the model objectives category (I), high level information from the HDV market diffusion literature is analysed such as the research question(s), country of observation and, time horizon. The authors believe that these parameters provide insights into the motivation and objectives of the studies. In addition, the geographic and time-related parameters help to interpret the data more accurately.

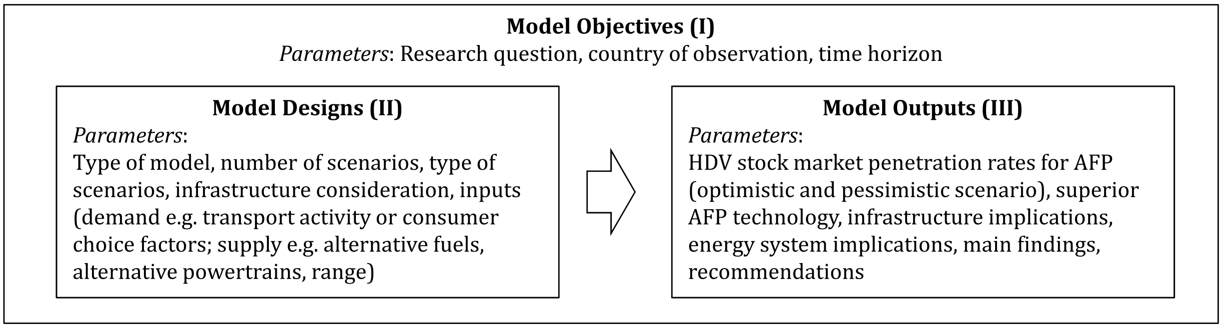


Fig. 3. General structure of considering market diffusion and parameters in this review.

The second category covers the model design and its input for market diffusion models (II). The analysis criteria here are the type of model, number and type of scenarios and consideration of historical data. The authors consider demand attributes (such as transport activity or customer choice factors), supply attributes (vehicle attributes such as fuel, powertrain, range, power, etc.) and framework factors (such as government policies or infrastructure) as inputs. On the one hand, the authors consider understanding a model to be beneficial when interpreting its outputs. On the other hand, it is expected that the input parameters reveal insights into the baseline and assumptions concerning the HDV sector and enable a better understanding and comparison of the starting point of the studies.

The third and final category combines analysis criteria for the model output factors (III), i.e. the results of modelling HDV market diffusion. Our focus is on AFP market penetration rates in HDVs for the different scenarios in the studies. To enable a comparison of scenarios across the various studies, the authors highlight the most optimistic scenario with a high AFP market share, and a pessimistic scenario with a low AFP market share per study. In addition, infrastructure and energy system implications are analysed as the authors consider them an important catalyst for any diffusion of AFPs. Finally, the data are also analysed regarding the main findings and recommendations. The authors expect insights into homogeneous statements, i.e. consistent opinions about the future of AFPs in HDVs, as well as heterogeneous statements.

2.3. Overview of market diffusion studies on HDV

In this section, the authors briefly summarize the relevant studies that projected the market diffusion of AFPs in the HDV segment.

Ambel (2017) focus on how to achieve zero GHG from road freight for Europe by 2050. Their bottom-up accounting tool EUTRM enables them to generate prognoses for traffic, energy and CO_2 emissions. Using the tool, Ambel (2017) define four scenarios from business-as-usual towards full electrification. Their analyses indicate an AFP share of up to 100% in the HDV stock by 2050.

Askin et al. (2015) develop a model to analyse technology and policy trade-offs for HDVs in the US. They construct a bottom-up consumer choice model to investigate the drivers for and barriers to the market diffusion of efficiency technologies and AFPs in HDVs. Modelling the HDV market, Askin et al. (2015) focus on US class 7 and 8 HDVs, define 4 different fleet sizes, and focus only on alternative fuels because these could quickly replace diesel in current ICE applications. In this model, infrastructure availability is a prerequisite for customer decisions in favour of AFPs and therefore a deal-breaker if not available. However, they exclude vehicle availability explicitly from the model indicating a made-to-order situation for consumers. Within their exploratory reference scenario, Askin et al. (2015) project an AFP market share of 11% in 2050.

Bahn et al. (2013) focus on the Canadian road sector and its potentials for electrification with AFPs. Their TIMES-Canada model is a bottom-up optimization model considering passenger vehicles as well as light, medium and heavy-duty freight vehicles. While FCEV and HYB AFP technologies are considered, Bahn et al. (2013) explicitly exclude BEV HDVs due to range limitations. They define two scenarios in addition to a reference scenario: One imposes targets for electric vehicle penetration and the other enforces targets for CO_2 emission reduction. Within the latter scenario, alternative fuels are assumed to dominate the HDV market by 2050.

Bründlinger et al. (2018) focus on the German 'Energiewende' (transition towards a renewables-based energy system) and include the decarbonization of the national transport sector. Their 'Dimension+' optimization model considers different modes of transport including on-road heavy-duty freight vehicles. In addition to a reference scenario, Bründlinger et al. (2018) consider four scenarios based on a matrix of technologies (pure electrification or technology mix) and the degree of decarbonization (80% or 95%). In their most optimistic scenario, AFP will reach a market share of 95% in 2050.

Çabukoglu et al. (2018) explore the maximum penetration depth for BEV–HDV under ideal conditions in Switzerland. Their bottom-up accounting model also considers total energy demand. Besides a current technology scenario, Çabukoglu et al. (2018) also use a maximum potential and battery swapping scenario. Their most optimistic scenario shows a share of up to 100% of AFPs in HDV stock.

Capros et al. (2016) calculate a price-indicated market balance and combine technological and economic parameters for various sectors including transport in the European Union. Their main tool, PRIMES, enables them to generate prognoses for traffic, energy and CO_2 emissions. Using the tool, Capros et al. (2016) follow a single reference scenario extrapolating current policies. As a result, their extrapolative analysis indicates an AFP share of 3% in the HDV stock in 2030.

Gambhir et al. (2015) analyse CO_2 emission and cost implications of AFPs for HDVs in the Chinese transport sector. Their bottom-up optimization model considers all types of road vehicles and clusters them into 9 classes, with HDV as one of them. Considering 5 AFPs in total, they explicitly include FCEV technology due to "growing interest". They also consider AFP infrastructure explicitly as an additional mark-up on fuel costs, and derive two scenarios: business-as-usual (BAU) and low-carbon. Their results present HYB as the predominant technology, accounting for up to 60% of the HDV stock in 2050.

Gerbert et al. (2018) look for the minimum cost way to lower CO_2 emissions in Germany without considering additional measures. Their VIEW model features a cohort model for the transport sector including passenger cars and trucks. Besides a reference scenario, Gerbert et al. (2018) also use a matrix logic for four additional scenarios covering two dimensions: regionality (national path or global path) and degree of decarbonization (80% or 95%). As a result, their most optimistic scenario shows an AFP share of up to 85% in HDV stock by 2040.

Kasten et al. (2016) focus on deriving a strategy for the CO_2-neutral energy supply of the transport sector in Germany until 2050. Their bottom-up TEMPS model covers multiple means of transport including trucks. The model sets the goal of carbon-neutral AFPs and derives four normative scenarios: power-to-liquid fuels, direct electrification, power-to-gas methane and power-to-gas hydrogen. The result of Kasten et al. (2016) is an AFP share of up to 95% using direct electrification with CAT HDVs.

Liimatainen et al. (2019) develop a methodology to estimate the potential of BEV–HDVs in Finland and Switzerland. They use a bottom-up accounting model to simulate four scenarios: current technology, improved vehicles, improved vehicles & charging, and towards full electrification. Within the most optimistic scenario, they forecast an AFP market share of about 60% in Finland and 68% in Switzerland.

Mai et al. (2018) aim to build an understanding of how the potential for HDV electrification might influence demand in the USA. Their bottom-up accounting model EnergyPathways sets three scenarios until 2050: Reference, medium and high. Within their most optimistic scenario, Mai et al. (2018) forecast an AFP market share of 41% in 2050.

Mulholl et al. (2018) assess the "long haul towards decarbonizing road freight" by calculating future energy needs and emissions in the respective sector on a global scale. Their Mobility Model, a bottom-up simulation model, focusses on the truck market, distinguishes light, medium and HDV and considers four AFPs for HDVs. Within their second – rather optimistic – scenario, a significant diffusion of CAT and HYB technologies is projected up to 2050. Mulholl et al. (2018) worked closely on study IEA (2017), "The Future of Trucks".

Naceur et al. (2017) focus on a cost-related optimization of the technology portfolio used in various industries on a global level. They apply a model combination of ETP (sales model) and MoMo (stock model) to model the HDV market in detail. Three scenarios are defined within their analyses: 'reference' (average temperature increase of 2.7 °C until 2100), '2 °C scenario' (maximum 2 °C increase) and 'beyond 2 °C' (maximum of 1.75 °C increase). The latter scenario results in an AFP market share of about 90% in HDV stock.

Özdemir (2011) develops a model-based scenario analysis covering technical, economic and environmental aspects and focussing on road transport in Germany. He uses the TIMES-D model to simulate four scenarios until 2030: baseline, free market, CO_2 emission restriction and technology-based. Within the most optimistic scenario, he forecasts an AFP market share of about 3% in 2030.

Plötz et al. (2019) evaluate the impact of CAT HDVs on European CO_2 emissions and its electricity system. They use a combined model (ALADIN, PERSEUS-EU) to model both the HDV sector and the electricity system. The study analyses four scenarios: a BAU energy system and a strong renewable energy system, both with and without the usage of CAT HDVs. Their scenarios result in comparatively similar AFP market diffusion rates of between 40% and 50% of the HDV stock in 2040.

Repenning et al. (2015) focus on cost-related optimization to reach CO_2 targets in Germany. Combining two models, TIMES and ASTRA-D, they analyse different sectors including the transport sector and focus on heavy-duty-vehicles. Using the same scenario set-up as Gerbert et al. (2018), they predict an AFP share of 100% in HDV stock by 2040.

Seitz (2015) analyses the diffusion of various innovative powertrain technologies to reduce the CO_2 emissions of freight vehicles in Germany. His bottom-up system dynamics model considers seven different types of heavy-duty vehicle and constructs four scenarios until 2030: baseline, CO_2 policy, e-mobility, and recession. Within his most optimistic scenario, AFPs reach a market share of 15% in 2030 with the HYB technology.

Siegemund et al. (2017) compare the investments and energy demand of different technologies in the transport sector of the EU. Their model considers passenger vehicles as well as light, medium and heavy-duty freight vehicles. Siegemund et al. (2017) define three scenarios: power-to-liquid, power-to-gas, and e-drive (direct electrification). Within their most optimistic scenario, they forecast an AFP market share of 95% in the HDV stock in 2050 based on FCEV technology.

Talebian et al. (2018) focus on the electrification of HDVs and the respective policy implications for one Canadian province. Their bottom-up accounting framework model considers class 8 HDVs and distinguishes them into nine sub-categories based on weight, roof height and cabin design. Within the two scenarios targeting the reduction of CO_2 emissions by more than 60%, only fully electrified powertrain options are considered. Since both scenarios set a large CO_2 reduction as an input parameter, they result in significant AFP market shares of more than 70% in 2040.

3. Results

In this section, the authors present the results of the literature review and compare the model objectives, model designs and model outputs of the analysed studies. In addition, the authors compare the main results and policy recommendations of all the reviewed literature.

3.1. Model objectives

When comparing the reviewed studies, it becomes clear that all the authors aim to gain insights into the reduction of CO_2 emissions in the HDV sector in the future and thus into the market diffusion of AFPs in HDV. Apart from this shared objective, some authors also target additional aspects, such as cost implications (Gambhir et al., 2015) or impacts on the energy system (Mai et al., 2018; Naceur et al., 2017; Plötz et al., 2019).

Most studies are in line with the time horizon of global climate targets, e.g. Capros et al. (2016). The observed time horizon runs from 2020 up to 2050 (in 12 studies). Özdemir (2011) and Seitz (2015) observe up to 2030, while Plötz et al. (2019) and Talebian et al. (2018) stop at the year 2040. Only (Naceur et al., 2017) forecasts until 2060. Çabukoglu et al. (2018) and Liimatainen et al. (2019) decouple HDV decarbonization from a timeline and refer to feasible potentials.

The studies cover different geographical scopes: These range from single countries, such as Canada (Bahn et al., 2013; Talebian et al., 2018), China (Gambhir et al., 2015), Germany (Bründlinger et al., 2018; Gerbert et al., 2018; Kasten et al., 2016; Özdemir, 2011; Repenning et al., 2015; Seitz, 2015), Switzerland (Çabukoglu et al., 2018; Liimatainen et al., 2019) or the US (Askin et al., 2015; Mai et al., 2018), through regions such as the EU28 (Ambel, 2017; Capros et al., 2016; Siegemund et al., 2017) up to a global perspective (Mulholl et al., 2018; Naceur et al., 2017). The German bias is probably due to the search languages used, even though the authors also tried other languages such as French or Spanish.

In sum, the research questions indicate that the reviewed studies have a similar motivation for the research conducted: the reduction of CO_2 emissions in HDVs until 2050. However, there is still a noticeable lack of current research on global HDV markets such as Africa, India, Middle East and Latin America, which account for about 30% of today's global HDV stock (IEA, 2017).

3.2. Model designs

Before comparing the outputs, the authors aimed to understand the structure of each model in order to address our second research question. According to Karnowski (2017), model design is separated into the two sub-sections 'model parameters' and 'input parameters'.

3.2.1. Model parameters

This section presents the modelling parameters of the existing market diffusion studies of AFPs in HDVs obtained by analysing the model type, modelled scenarios, sectoral scope and the economic perspective.

In order to classify the model types used in the literature, the authors applied the framework developed by Gnann and Plötz (2015). This framework defines bottom-up models as a combination of individual assumptions to generate an aggregated outcome with a strong focus on technologies. All the models used in the analysed studies are bottom-up. As shown in Table 3, half of them use bottom-up simulation models to reconstruct behavioural processes based on either individual agents or systemic rules (system dynamics). The other half use either a bottom-up optimization model, which optimizes supply and demand to reach an economic optimum, or a bottom-up accounting framework to determine sectoral outcomes (e.g. transport and industrial production sector). One of the non-peer-reviewed studies does not provide any information about the model used.

All the models construct between one and five scenarios. The majority of models provide a reference scenario as a baseline and add scenarios with increasing CO_2 emission restriction. Ten of the models with at least two scenarios define the reference scenario as an exploratory scenario, while the other scenario(s) is (are) normative. Exploratory scenarios describe potential future developments based on known processes, current trends or causal dynamics and generate a forecast, while normative scenarios are prescriptive, using a future target and backcasting to develop scenarios (McCarthy et al., 2018). The normative scenarios mainly set single dimensional target fulfilment (CO_2 emission target) on different levels e.g. 80% or 95% CO_2 emission reduction in 2050. Table 4 shows the policies considered to reach the normative scenarios. Most authors do not specify the policy level needed to reduce CO_2 emissions; however, some researchers focus on sector-specific policies, e.g. vehicle efficiency standards or fuel taxes. Additionally, two studies considered existing restrictions regarding particulate matter (Askin et al., 2015; Mulholl et al., 2018).

Six studies specifically model the truck transport sector (Ambel, 2017; Askin et al., 2015; Mulholl et al., 2018; Plötz et al., 2019; Seitz, 2015; Talebian et al., 2018), while all others also model the passenger transport sector or even non-road transport sectors such as trains, planes and ships.

Most models take a macro-economic perspective i.e. they determine an overall economic optimum. This perspective looks for a holistic optimum for the region analysed without considering controlling elements such as taxes or subsidiaries. In contrast, Askin et al. (2015), Repenning et al. (2015) do not take this perspective; their models consider taxes. In addition, there are no clear references to the perspective taken in Seitz (2015), Talebian et al. (2018).

In summary, researchers use different types of bottom-up model (simulation, optimization, and accounting framework) to determine market diffusion, and generally between three and five scenarios.

3.2.2. Input parameters

The authors look at two key input parameters: supply and demand.

The technologies and their CO_2 emissions are common supply input parameters when modelling the market diffusion of AFPs in HDVs. As outlined in the Introduction, ten AFP technologies are considered in addition to today's predominant diesel technology: six alternative fuels (LPG, LNG, CNG, eMET, eSYN, BIO) and four electrified powertrains (CAT, BEV, HYB, FCEV). CNG, HYB and FCEV receive the most attention, with a citation rate of about 60% (9/15), 53% (8/15) and 46% (7/15), respectively, as shown in Table 5.

Studies published in 2013 or earlier have a stronger focus on alternative fuels as an option to reduce CO_2 emissions, while the literature from 2015 and later tends to focus more on electrified powertrains. Repenning et al. (2015) are the first to mention the CAT powertrain; all other studies dealing with CAT were published from 2017 onwards. A more recent emphasis in the research aiming to reduce CO_2 emissions from transport is on electrifying HDV powertrains. Besides considering the CO_2 emissions of technologies, vehicle range is frequently mentioned when evaluating AFPs (in most cases, the BEV powertrain is excluded for HDV applications due to its low range). Additional potential customer requirements, such as vehicle power or refuelling/recharging time, are not mentioned in more recent publications, but were before 2015 (Askin et al., 2015; Özdemir, 2011; Seitz, 2015). Vehicle auxiliaries were considered heterogeneously and only mentioned in a minority of the reviewed studies. However, we could not find any connection between consideration of auxiliaries and the market diffusion of AFP or other reviewed criteria. On average, a single AFP technology was mentioned only in 50% of the studies or even less (cf. Table 6).

The reviewed studies agree that future demand for HDVs will grow. While the literature before 2015 did not state specific vehicle numbers or ton kilometres (tkm), more recent publications expect the stock to grow by at least 20% until 2050 (Askin et al., 2015; Talebian et al., 2018).

The framework parameters within the reviewed literature mainly concern currently implemented CO_2 emission policies. In contrast, consumer choice factors are generally disregarded (see Table 7). Most authors do not include range anxiety, vehicle availability, decision alternatives or technology improvements, even though these parameters are recommended by the research conducted on passenger vehicles (Gnann and Plötz, 2015). Most studies mention the infrastructure for AFPs, but only four indicate its respective cost (Bründlinger et al., 2018; Gambhir et al., 2015; Gerbert et al., 2018; Kasten et al., 2016), mainly by applying a mark-up on fuel and electricity prices. None of the studies consider the physical ramping up of additional electricity provision to supply AFP-HDVs, i.e. power grid expansion. The interdependency of market diffusion and infrastructure is not explicitly modelled in any of the reviewed studies.

In sum, all the reviewed studies project that the future HDV volume will grow significantly. However, other input factors vary strongly. The AFPs considered by researchers are manifold and not homogeneous. Further, the majority of studies do not consider AFP infrastructure and its energy supply.

3.3. Model outputs

In this section, the authors review a specific output of the analysed models: the market diffusion of AFPs in HDVs.

In order to be able to compare the studies and their scenarios, the authors categorize the scenario results into two clusters. All exploratory reference scenarios are categorized within the cluster "reference scenario". The most AFP-positive scenarios are

Table 3
Overview of model design, scenarios and other model parameters.

Author	Model name	Model type	Modelled scenarios	Scenario classification	Other transport modes included?	Macro-economic perspective?
Ambel (2017)	EUTRM	Accounting framework	4 scenarios (BAU, low hanging fruit, LHF + partial electrification, LHF + full electrification)	BAU scenario is explorative, other 3 are normative	No	Yes
Askin et al. (2015)	(no name)	Simulation model	2 scenarios (baseline, exaggerated)	Both scenarios are explorative	No	No
Bahn et al. (2013)	TIMES-Canada	Optimization model	3 scenarios (baseline, energy policy, climate policy)	BAU scenario is explorative, other 2 are normative	Yes	Yes
Bründlinger et al. (2018)	DIMENSION+	Optimization model	5 scenarios (Reference, matrix of electrification and technology max with 80% and 95%)	Reference scenario is explorative, other 4 scenarios are normative	Yes	Yes
Çabukoglu et al. (2018)	(no name)	Accounting framework	3 (current technologies, max. potential, battery swapping)	Current technologies scenario is explorative, other 2 are normative	Yes	Yes
Capros et al. (2016)	PRIMES-TREMOVE	Simulation model	1 scenario (reference)	Reference scenario is explorative	Yes	Yes
Gambhir et al. (2015)	(no name)	Optimization model	2 scenarios (BAU, low-carbon)	Both scenarios are normative	Yes	Unclear
Gerbert et al. (2018)	VIEW	Simulation model	5 scenarios (reference, matrix of national go-it-alone and global way with 80% and 95%)	Reference scenario is explorative, other 2 scenarios are normative	Yes	Yes
Kasten et al. (2016)	TEMPS	Accounting framework	4 scenarios (FI+, E+, CH4+, H2+)	All 4 scenarios are normative	Yes	Yes
Liimatainen et al. (2019)	(no name)	Accounting framework	4 Scenarios (current technology, improved vehicles, IV & charging, towards full electrification)	Current technologies scenario is explorative, other 3 are normative	Yes	Yes
Mai et al. (2018)	EnergyPath-ways	Accounting framework	3 scenarios (reference, medium, high)	Reference scenario is explorative, other 2 are normative	Yes	Yes
Mulholl et al. (2018)	MoMo	Simulation model	2 scenarios (COP21, modern)	Reference scenario is explorative, other scenario is normative	No	Yes
Naceur et al. (2017)	ETP model	Optimization model	3 scenarios (RTS, 2DS, B2DS)	RTS scenario is explorative, other 2 scenarios are normative	Yes	Yes
Özdemir (2011)	TIMES-D	Simulation model	4 scenarios (baseline, free market, GHG emission restriction, technology based)	Base scenario is explorative	Yes	Yes
Plötz et al. (2019)	ALADIN, PERSEUSEU	Simulation model	4 scenarios (matrix of optimistic with pessimistic)	Both scenarios are explorative	No	Yes
Repenning et al. (2015)	TEMPS, ASTRA-D	Accounting framework	3 scenarios (baseline, 80%, 95%)	Reference scenario is explorative, other 2 scenarios are normative	Yes	No
Seitz (2015)	(no name)	Simulation model	4 scenarios (baseline, CO2-policy, e-mobility, recession)	All 4 scenarios are explorative	No	Unclear
Siegemund et al. (2017)	[none]	[no info]	3 scenarios (PtL, PtG, eDrive)	All 3 scenarios are normative	Yes	Yes
Talebian et al. (2018)	(no name)	Accounting framework	2 scenarios (BAU, CLF)	Both scenarios are normative	No	Yes

clustered under "climate protection scenario" (these scenarios are mainly normative, only Askin et al., 2015 and Plötz et al., 2019 defined a second AFP-optimal exploratory scenario). These two clusters are shown in Fig. 4, which shows the share of AFPs in the HDV stock in percent on the y-axis and the timeline from 2020 to 2060 on the *x*-axis. Both graphs in Fig. 4 contain boxplots only from 2020 to 2050, because there are not enough data points in the studies for 2020 (mainly 0% market share for AFPs) and 2060 (only one study with data). The exact scenario names, market share figures and most competitive AFPs can be found in Tables 10 and 11 in the Annex.

In the reference scenario cluster (left-hand side in Fig. 4) and hence following an exploratory trajectory, the majority of studies forecast that AFPs will reach a maximum HDV market share of 20% by 2050. Only (Repenning et al., 2015) and (Plötz et al., 2019) see a potential market share of 30%–40% in their exploratory reference scenarios. The median of the reference scenario reaches 3% in 2030, 10% in 2040, and 11% in 2050.

However, in the climate protection scenario cluster, the market shares of AFPs in the HDV stock are projected to reach more than 60% in 2050. The studies diverge with regard to the most competitive AFP. While alternative fuels dominate diesel in the research conducted before 2016 (Askin et al., 2015; Bahn et al., 2013; Capros et al., 2016; Özdemir, 2011), alternative electrified powertrains are more competitive in more recent publications. The difference between the maximum and minimum whiskers declines from 76% in 2020 to 40% in 2050, with a median of 20% (2020) to 85% (2050).

Both the reference and the climate protection scenarios are consistent on a geographic level, i.e. the market penetration range is similar for the single country models such as China, Germany and the US, as well as the multi-regional models such as the EU-28. Further, most studies have a preferred AFP for both reference and climate protection scenario. Only two studies see for both scenarios different AFP as most competitive as shown in Table 8.

Table 4
Policy level consideration.

Author	Policy level consideration
Ambel (2017)	Yes, CO_2 emission regulations (no specification)
Askin et al. (2015)	Yes, CO_2 emission regulations (vehicle efficiency) and local pollution (particulate matter)
Bahn et al. (2013)	Yes, CO_2 emission regulations and e-vehicle market diffusion regulations
Bründlinger et al. (2018)	No
Çabukoglu et al. (2018)	Yes, CO_2 emission regulations (no specification)
Capros et al. (2016)	Yes, CO_2 emission regulations (no specification)
Gambhir et al. (2015)	No
Gerbert et al. (2018).	Yes, CO_2 emission regulations (no specification)
Kasten et al. (2016)	No
Liimatainen et al. (2019)	Yes, CO_2 emission regulations (no specification)
Mai et al. (2018)	Yes, CO_2 emission regulations (no specification)
Mulholl et al. (2018)	Yes, CO_2 emission regulations (fuel economy regulations, carbon taxes on transport fuels) and local pollution (particulate matter)
Naceur et al. (2017)	Yes, CO_2 emission regulations (no specification)
Özdemir (2011)	Yes, CO_2 emission regulations (no specification)
Plötz et al. (2019)	Yes, CO_2 emission regulations (CO2-certificate prices, fuel prices)
Repenning et al. (2015)	Yes, CO_2 emission regulations (no specification)
Seitz (2015)	Yes, CO_2 emission regulations (CO2-certificate prices)
Siegemund et al. (2017)	Yes, CO_2 emission regulations (no specification)
Talebian et al. (2018)	Yes, CO_2 emission regulations (no specification)

Table 5
AFPs considered in the reviewed literature and the reasoning for this selection.

Author	Diesel	LPG	LNG	CNG	e-Methan	e-Synfuels	Biofuels	Catenary (Electricity)	BEV (Electricity)	Hybrid (incl. Plugin)	FCEV (Hydrogen)	Reasoning for selection
Ambel (2017)	√	–	–	–	–	–	–	√	√	–	–	Only full-electrified options considered, due to efficiency
Askin et al. (2015)	√	–	√	√	–	–	–	–	–	–	–	Only LNG and CNG due to possibility of fast switch from Diesel
Bahn et al. (2013)	√	–	–	–	–	√	√	–	–	√	√	BEV excluded due to battery capacity limitations
Bründlinger et al. (2018)	√	–	√	√	√	–	–	–	√	√	√	Catenary only for sensitivity analyses
Çabukoglu et al. (2018)	√	–	–	–	–	–	–	–	√	–	–	Only BEV to focus on their potential
Capros et al. (2016)	√	–	√	–	–	–	–	–	–	–	–	Hydrogen excluded due to lack of adopted policies
Gambhir et al. (2015)	√	√	–	√	–	–	–	–	√	√	√	Hydrogen included due to growing interest
Gerbert et al. (2018)	√	–	–	√	–	–	–	√	–	√	√	BEVs excluded due to range, FCEVs included therefore
Kasten et al. (2016)	√	–	–	–	√	√	–	–	√	–	√	No reason given
Liimatainen et al. (2019)	√	–	–	–	–	–	–	–	√	–	–	BEV are technically and commercially viable
Mai et al. (2018)	√	–	–	–	–	–	–	–	√	–	–	No reason given
Mulholl et al. (2018)	√	–	√	√	–	–	√	√	–	√	–	No reason given
Naceur et al. (2017)	√	√	–	√	–	–	–	√	√	√	–	FCEV excluded due to uncertainties and lower efficiency than catenary
Özdemir (2011)	√	–	–	√	–	–	√	–	–	√	–	No reason given
Plötz et al. (2019)	√	–	–	–	–	–	–	√	–	–	–	No reason given
Repenning et al. (2015)	√	–	–	√	–	–	√	√	–	√	–	BEV excluded, due to battery range and weight
Seitz (2015)	√	–	√	√	–	–	–	–	√	–	–	No reason given
Siegemund et al. (2017)	√	–	–	–	√	–	–	–	–	–	√	BEVs excluded due to range, therefore FCEVs included
Talebian et al. (2018)	√	–	–	–	–	–	–	–	√	–	√	Only fully-electrified options considered due to efficiency
Total	19/19	2/19	5/19	9/19	3/19	2/19	4/19	6/19	10/19	8/19	8/19	

The model outputs paint a clear picture: Without additional (policy) measures, the underlying market share of AFPs in the HDV stock will be less than 40% and the CO_2 emission targets will not be met. In contrast, with increased efforts to meet the

Table 6
Share of AFP mentioned throughout all reviewed studies (e.g. BEVs were considered in about 50% of all reviewed studies).

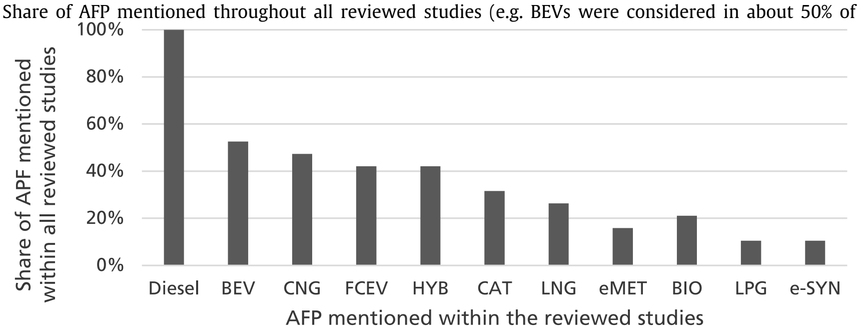


Table 7
Consumer choice factors considered.

Author	Consumer choice factors			
	Range anxiety	Vehicle availability	Decision alternatives	Technology improvements
Ambel (2017)	–	–	–	–
Askin et al. (2015)	–	Yes, infrastructure availability is basis for consumer decisions	Yes, willingness to consider an alternative fuel based on infrastructure availability	–
Bahn et al. (2013)	–	–	–	–
Bründlinger et al. (2018)	–	–	–	–
Çabukoglu et al. (2018)	–	–	–	√
Capros et al. (2016)	–	–	–	–
Gambhir et al. (2015)	–	–	–	–
Gerbert et al. (2018).	–	–	–	–
Kasten et al. (2016)	–	–	–	√
Liimatainen et al. (2019)	–	–	–	√
Mai et al. (2018)	–	–	–	–
Mulholl et al. (2018)	–	–	–	–
Naceur et al. (2017)	–	–	–	–
Özdemir (2011)	–	–	–	–
Plötz et al. (2019)	–	√	√	√
Repenning et al. (2015)	–	–	–	–
Seitz (2015)	–	–	√	–
Siegemund et al. (2017)	–	–	–	–
Talebian et al. (2018)	–	–	–	–

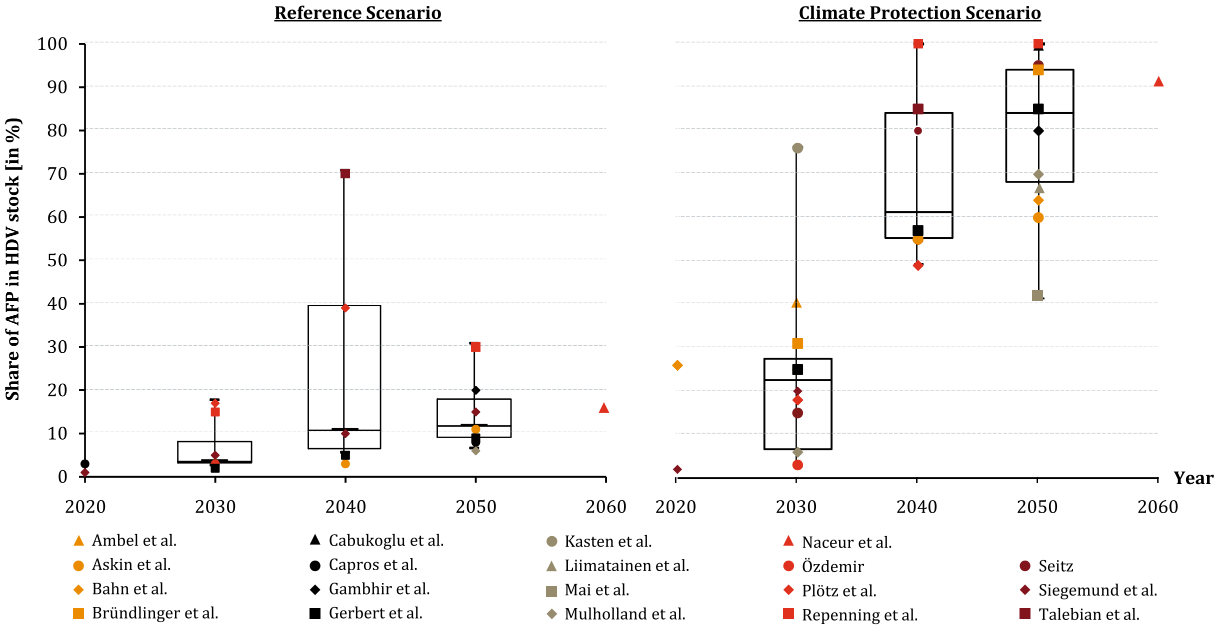


Fig. 4. Market diffusion of AFP over time in reference and climate protection scenarios. Shown are boxplots of the studies for share of AFP vehicles in stock in different years. The whiskers show the minimum and maximum of all results, while the box contains all values between the quartiles. The solid line represents the median.

Table 8
Focus regions and most competitive AFP per scenario (reference and climate protection).

Author	Most competitive AFP (reference scenario)	Most competitive AFP (climate protection scenario)
Ambel (2017)	[none]	BEV
Askin et al. (2015)	NGV	NGV
Bahn et al. (2013)	BIO	BIO
Bründlinger et al. (2018)	FCEV	FCEV
Çabukoglu et al. (2018)	[none]	BEV
Capros et al. (2016)	LNG	LNG
Gambhir et al. (2015)	HYB	HYB
Gerbert et al. (2018).	HYB	CAT
Kasten et al. (2016)	HYB or CAT	CAT
Liimatainen et al. (2019)	[none]	BEV
Mai et al. (2018)	[none]	BEV
Mulholl et al. (2018)	HYB	CAT
Naceur et al. (2017)	HYB	HYB or CAT
Özdemir (2011)	[none]	CNG
Plötz et al. (2019)	CAT	CAT
Repenning et al. (2015)	BIO	CAT
Seitz (2015)	[none]	HYB
Siegemund et al. (2017)	eMET	FCEV
Talebian et al. (2018)	BEV or FCEV	BEV or FCEV

CO_2 emission targets, more than 60% AFPs in the HDV stock seem feasible. However, there is no consensus about which technology prevails.

3.4. Comparison of main findings

This section reviews the main findings of the AFP market diffusion literature for HDVs, which can be summarized in five categories.

First, all the researchers emphasize diesel ICE dominance: In the exploratory reference scenarios, the diffusion of AFPs in the HDV market is limited to a maximum of 40% within the next three decades. Hence, ICE technology with diesel will remain dominant for HDVs.

Second, even though decoupling energy consumption and driving activity is projected to increase, the studies state that "decarbonization falls short on agreed targets" (Capros et al., 2016), with current policies aiming at greater fuel efficiency of conventional HDVs (Talebian et al., 2018). Alongside improving efficiency and operations, Mulholl et al. (2018) conclude that AFPs are the largest lever in HDV decarbonization. However, simply using alternative fuels will not be sufficient to meet the CO_2 emission targets (Askin et al., 2015) and there is an additional need for alternative electrified powertrains with "noteworthy" CO_2 emission reduction potentials (Plötz et al., 2019).

Third, optimal and non-optimal niches are mentioned. Kasten et al. (2016) says that FCEV powertrains are more cost effective for long-haul applications due to comparatively high initial vehicle investments. For urban or short-haul applications, Çabukoglu et al. (2018) and Seitz (2015) find BEV HDVs rather attractive for short ranges, while Askin et al. (2015) prefers CNG here.

Fourth, there are statements regarding economic optima, which are derived from normative scenarios using bottom-up optimization models. Accordingly, the direct use of electricity represents the most cost-effective supply of energy (Kasten et al., 2016). Furthermore, raising diesel prices (Capros et al., 2016) while minimizing additional vehicle investments (Askin et al., 2015) is the most effective approach when aiming for fast AFP market diffusion.

The fifth main finding concerns the implications for the energy system. The reviewed studies agree that the (HDV) transport sector will become an additional electricity market participant in the future. However, they gauge the impact of AFP-HDVs on the electric load very differently — from "limited" (Plötz et al., 2019) to "major" (Siegemund et al., 2017).

3.5. Comparison of policy recommendations

Besides the market diffusion of AFPs in the HDV sector, most studies also draw policy conclusions from their modelling efforts, which are compared in this section.

The recommendations mainly address industry and policy makers. Industry recommendations generally focus on reducing the costs of vehicle investments, e.g. by implementing large-scale AFP vehicle platforms in the HDV sector or reducing battery costs (Seitz, 2015). There are four main recommendations for policy makers: use subventions to support R&D and production funding (Özdemir, 2011; Talebian et al., 2018); ease weight regulations (Çabukoglu et al., 2018); encourage customers to prolong depreciation rates (Askin et al., 2015); and tighten CO_2 emission regulations (Mai et al., 2018; Mulholl et al., 2018). Other recommendations target general topics such as supporting information and data collection to obtain more research insights into AFP for HDVs (Mai et al., 2018; Naceur et al., 2017).

Finally, most researchers point to the risk of not meeting the CO_2 emission reduction targets if AFPs diffuse too slowly through the stock of HDVs and therefore make recommendations on how to speed this up. However, there is no consensus among the reviewed studies concerning either a single, superior AFP technology for the HDV sector, nor a set of policies to accelerate the market diffusion of AFP for HDVs.

4. Summary and discussion

In summary, the authors draw four main findings from this review. First, most studies forecast that AFPs in HDVs will already diffuse into the market within exploratory (reference) scenarios to a maximum of 30% by 2050 (10% market diffusion at 25% quartile of all reviewed studies). This implies that today's market environment is already fostering the transition towards AFPs in HDVs. Second, AFPs dominate the CO_2 emission reduction (climate protection) scenarios, with all studies forecasting an AFP market diffusion of more than 40% (Fig. 4), indicating the positive impact of AFPs on climate protection. Without additional (policy) measures, the share of AFPs in the HDV sector will remain low, and the 2050 climate targets will not be met. Our third main finding concerns the high technological uncertainty, which becomes apparent when evaluating the AFPs in the reviewed literature. There are differences, for instance, concerning BEVs (some studies do not consider BEVs at all (cf. Bahn et al., 2013), others only consider fully electrified HDVs due to their high efficiencies Talebian et al., 2018), FCEV (some studies exclude the technology due to the lack of adopted policies Capros et al., 2016) and the technological readiness of CAT. Therefore, there are very diverse results regarding the most competitive AFP technology. Our fourth finding concerns how important criteria are addressed in market penetration models. The TCO are considered in all the models, but other criteria are not, such as infrastructure costs or energy system implications. Infrastructure ramp-up costs are proportionally higher at an early market diffusion stage than in a steady state (Robinius et al., 2018) and therefore have a significant impact on the market diffusion of AFPs. Likewise, adapting the energy system to AFPs may be crucial for the successful introduction of new energy carriers, e.g. hydrogen (Hanley et al., 2018). However, as Table 9 clearly shows, the majority of the reviewed literature does not consider either infrastructure or the impacts on the energy system.

Our review also identified four major limitations. The first is the diverse regional definition of HDVs. Even though the authors

Table 9
Literature overview of infrastructure and energy system modelling.

Author	Infrastructure modelled?	Energy system modelled?
Ambel (2017)	–	–
Askin et al. (2015)	–	–
Bahn et al. (2013)	–	- (only total energy demand determined)
Bründlinger et al. (2018)	–	- (only total energy demand determined)
Capros et al. (2016)	–	√
Gambhir et al. (2015).	–	–
Gerbert et al. (2018)	–	–
Kasten et al. (2016)	√	–
Liimatainen et al. (2019)	√	–
Mai et al. (2018)	–	- (only total energy demand determined)
Mulholl et al. (2018)	–	–
Naceur et al. (2017)	–	- (only total energy demand determined)
Özdemir (2011)	–	–
Plötz et al. (2019)	–	√
Repenning et al. (2015)	–	- (only total energy demand determined)
Seitz (2015)	–	–
Siegemund et al. (2017)	–	- (only total energy demand determined)
Talebian et al. (2018)	–	- (only total energy demand determined)

Table 10
Market share of AFP in reference scenarios and most competitive AFP.

Author	Focus region	Name of reference scenario	AFP share in % (reference scenario)					Most competitive AFP (reference scenario)
			2020	2030	2040	2050	2060	
Ambel (2017)	EU-28	Business-as-usual	–	–	–	–	–	[none]
Askin et al. (2015)	USA	Reference	–	3	6	11	–	NGV
Bahn et al. (2013)	Canada	Business-as-usual	–	–	–	–	–	BIO
Bründlinger et al. (2018)	Germany	Reference	–	–	–	–	–	FCEV
Çabukoglu et al. (2018)	Switzerland	Current technologies	–	–	–	–	–	[none]
Capros et al. (2016)	EU-28	Reference	0	3	–	8	–	LNG
Gambhir et al. (2015)	China	Business-as-usual	0	–	–	20	–	HYB
Gerbert et al. (2018).	Germany	Reference	0	2	5	9	–	HYB
Kasten et al. (2016)	Germany	Baseline	0	–	–	30	–	HYB or CAT
Liimatainen et al. (2019)	Finland & Switzerland	Current technologies	–	2	–	–	–	[none]
Mai et al. (2018)	USA	Reference	–	–	–	0%	–	[none]
Mulholl et al. (2018)	Global	Reference	–	2	–	6	–	HYB
Naceur et al. (2017)	Global	RTS	–	–	–	–	17	HYB
Özdemir (2011)	Germany	Baseline	0	0	–	–	–	[none]
Plötz et al. (2019)	EU-28	Pessimistic	0	17	39	–	–	CAT
Repenning et al. (2015)	Germany	[none]	–	–	–	30	–	BIO
Seitz (2015)	Germany	Non-intervention	–	–	–	–	–	[none]
Siegemund et al. (2017)	EU-28	PtL	1	5	10	15	–	eMET
Talebian et al. (2018)	Canada	CLF	0	–	70	–	–	BEV or FCEV

searched official vehicle categories, HDVs still vary regionally, e.g. by permitted axle load and vehicle length. The consequence is that one AFP technology might suitable for HDVs in one region but not in another due to weight and volume restrictions. Second, the market phase for AFPs in HDV is still at an early stage (with nearly 100% of the stock running on conventional diesel fuel), implying comparatively low technological maturity but growing visibility of the topic. This may lead study authors to be overly optimistic about future developments (cf. Gartner hype cycle, Perez and Kreinovich, 2018). Third, our limited search terms and search language mean the authors may have missed key research studies. Finally, the authors may also have missed additional relevant criteria for the analyses (cf. Gnann et al., 2018).

5. Recommendations for further research

In this paper, the authors compared 19 research publications modelling the market diffusion of AFPs in HDVs. The authors synthesized the similarities and differences of objectives, model designs and outputs, and discussed them to derive the following five recommendations for further research:

1. *Perform more research on AFP technologies:* The current research considers multiple AFPs and gives no clear indication which is the most suitable to decarbonize HDVs. None of them seems superior for either a significant market segment or the sector as a whole. Further research addressing vehicle design and economic viability may provide clearer indications (Kast et al., 2017; Connolly, 2017; Mai et al., 2018).
2. *Assess the impact of individual policies on AFP market diffusion in the HDV sector*: The reviewed literature clearly emphasizes the positive effect of CO_2 regulations on accelerating AFP market diffusion. However, none of the studies evaluates the individual impact of policies such as CO_2 standards (with different levels), toll exemption or zero emission zones.
3. *Take infrastructure development and energy supply into account:* Regarding the modelling approach, the authors recommend acknowledging the fact that HDVs will become a relevant player in the electricity market. This means that the modelling input parameters and model design should consider the power system, energy transport and distribution as well as the fuelling and charging infrastructure (as the element connecting the transportation industry and the power system).

Table 11
Market share of AFP in climate protection scenarios and most competitive AFP. The normative goal describes the objective that is set by the study authors until their final year of forecast, e.g. a 95% CO_2 emission reduction (*−95%* CO_2).

Author	Focus region	Name of climate protection scenario	AFP share in % (climate protection scenario)					Most competitive AFP (climate protection scenario)
		(normative goal)	2020	2030	2040	2050	2060	
Ambel (2017)	EU-28	LFH + full electrification	1%	40%	–	–	–	BEV
Askin et al. (2015)	USA	Exaggerated (*no information*)	–	25	55	60	–	NGV
Bahn et al. (2013)	Canada	CLIM (*−50%* CO_2)	26	–	–	64	–	BIO
Bründlinger et al. (2018)	Germany	EL95 (*−95%* CO_2)	–	31	–	94	–	FCEV
Çabukoglu et al. (2018)	Switzerland	Battery swapping	1%	–	–	100%	–	BEV
Capros et al. (2016)	EU-28	[none]	0	–	–	–	–	LNG
Gambhir et al. (2015)	China	95% Target (*−95%* CO_2)	0	–	–	80	–	HYB
	Germany	95% Target (*−95%* CO_2)	0	25	57	85	–	CAT
Kasten et al. (2016)	Germany	95% Target (*−95%* CO_2)	0	0	80	95	–	CAT
Liimatainen et al. (2019)	Finland & Switzerland	Towards full electrification	–	–	–	60% [F] 68% [CH]	–	BEV
Mai et al. (2018)	USA	High	–	–	–	41%	–	BEV
Mulholl et al. (2018)	Global	Modern (*−95%* CO_2)	–	6	–	70	–	CAT
Naceur et al. (2017)	Global	B2DS (*−95%* CO_2)	–	–	–	–	91	HYB or CAT
Özdemir (2011)	Germany	GHG (*−53%* CO_2)	0	3	–	–	–	CNG
Plötz et al. (2019)	EU-28	Optimistic	0	18	49	–	–	CAT
Repenning et al. (2015)	Germany	All scenarios (*−95%* CO_2)	0	76	100	100	–	CAT
Seitz (2015)	Germany	[none]	0	15	–	–	–	HYB
Siegemund et al. (2017)	EU-28	eDrive (*−95%* CO_2)	2	20	55	95	–	FCEV
Talebian et al. (2018)	Canada	Business-as-usual (*−64%* CO_2)	0	–	85	–	–	BEV or FCEV

4. *Combine different methods:* Future research should investigate whether combining multiple models (e.g. simulation and optimization models or optimization and accounting framework models) has advantages over using individual bottom-up models. Such combinations may generate new insights into the market diffusion process. Additionally, models with greater consideration of consumer requirements may be beneficial, similar to the passenger vehicle models available (Gnann et al., 2018).
5. *Increase the use of sensitivity analyses:* Varying key input parameters in sensitivity analyses could generate more insights into the drivers for or barriers to the market diffusion of AFPs in HDVs. The reviewed literature did not perform sensitivity analyses consistently. Thus, statements regarding the impact of parameter variations are limited, and key sensitive parameters were largely not identified.
6. *Consider additional key markets:* The authors recommend an additional focus on HDV markets such as Africa, India, the Middle East, Latin and South America when modelling the future market diffusion of AFP in HDVs. These countries account for about 30% of the global HDV stock and may offer further insights into the future development of AFPs in HDVs due to their specific circumstances regarding stock structure, annual mileages and energy prices.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix

See Tables 10 and 11.

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