Cost-effective technology choice in a decarbonized and diversified long-haul truck transportation sector: A U.S. case study

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Abstract

Achieving net-zero emissions by 2050 will require accelerated efforts that include decarbonizing long-haul road transportation. In this difficult-to-decarbonize, low-margin industry, economic transparency on technology options is vital for decision makers seeking to eliminate emissions. Battery electric (BET) and hydrogen fuel cell electric trucks (FCET) can represent emission-free alternatives to diesel-powered trucks (DT). Previous studies focus on cost competitiveness in weight-constrained transportation even though logistics research shows that significant shares of transportation are constrained by volume, and analyze cost only for selected technologies, hence impeding a differentiated market segmentation of future emission-free trucks. In this study, the perspective of a rational investor is taken and it is shown that, under current conditions in the U.S., BETs outperform FCETs in various long-haul use cases despite charging times and cargo deficits, and will further increase their technological competitiveness to DTs. While future energy and fueling prices are decisive for BET competitiveness, the analysis reveals that autonomous driving may change the picture in favor of FCETs.

Highlights

- Battery electric trucks on the verge of competitiveness at trip distances <500 km
- LFP-based chemistries are more suitable for volume-constrained transports
- High-Nickel-based chemistries are suitable for weight-constrained transports
- Fuel cell closest to diesel parity for weight-constrained transports >600 km
- U.S. energy prices to be reduced for battery and/or fuel cell competitiveness vs. diesel
- Autonomous driving will particularly improve fuel cell truck competitiveness

Keywords

Battery electric truck; hydrogen fuel cell electric truck; long-haul transportation; cost-effective technology choice; total cost of ownership; mobility transition;

Wordcount

6,129 words

Abbreviations

BET	Battery electric truck
C	Graphite
CaT	Catenary truck
CE	Coulombic efficiency
CO_2	Carbon dioxide
DT	Diesel truck
FC	Fuel cell
FCET	Fuel cell electric truck
GVW	Gross vehicle weight
H_2	Hydrogen
HyT	Hybrid truck
kWh	Kilowatt hour
LFP	Lithium iron phosphate
LCO	Lithium cobalt oxide
LIB	Lithium-ion battery
NCA	Lithium nickel cobalt aluminum oxide
NGT	Natural gas truck
Ni	Nickel
NMC	Lithium nickel manganese cobalt oxide
R&D	Research and development
SEI	Solid electrolyte interface
SOP	Start of production
Ta	Tantalum
TCO	Total cost of ownership
VE	Voltage efficiency

1. Introduction

The decarbonization of the long-haul transportation sector is a key requirement to achieve net-zero emission goals by 2050 [1,2]. While cargo trucks account for 9% of the global vehicle stock, they generate 39% of the sector's greenhouse gas emissions [3]. In the U.S., heavy-duty trucks account for more fuel consumption and respective greenhouse gas emissions than all lighter truck categories combined [4] and hence, alternatives to diesel trucks (DT) offer significant climate and air quality benefits [5,6]. Among various alternatives, the International Energy Agency assigns the highest importance for net-zero emission to battery-electric trucks (BET) and hydrogen fuel cell electric trucks (FCET) [7], both allowing for carbon-neutral operation if renewable sources provide the required electricity for charging and hydrogen production [8]. Despite a greater reduction potential per vehicle compared to the light-duty segment, the adoption of these trucks proceeds at a slower pace [6,9]. In addition to a still limited offer of respective vehicles on the market [10] and concerns regarding infrastructure availability [11,12], customers face a lack of full economic transparency to compare truck propulsion technology options in their investment decision [13]. In this risk-averse [13], difficult-to-decarbonize [14,15] industry characterized by low profit margins, total cost of ownership (TCO, consisting of capital and operating cost [16]) represents the prior criterion for truck purchase decisions [17]. While TCO is a rational decision criterion on the currently diesel-dominated market, it needs to be complemented with regard to a more diverse set of future technology options. In addition to TCO differences that have been analyzed in multiple studies, long-haul BETs require significant charging times and, BETs and FCETs differ in powertrain weight and volume from DTs. Idle times induced by charging and cargo capacity deviations due to legal limits of gross vehicle weight and length result in profit differences that decision makers need to take into account and have to date not been comprehensively analyzed between BETs, FCETs and DTs. In addition, currently commercialized BETs differ in the battery chemistry used, and can be categorized in lithium iron phosphate (LFP)-based and High-Nickel-based BETs. While LFP chemistries offer safety and durability advantages [18] and are considered particularly suitable for heavy-duty applications [19], High-Nickel-based chemistries exhibit increased energy density that allows for higher payloads [20]. The impact of the choice of battery chemistry on BET competitiveness has so far not been investigated. Further, previous studies focus on weight-constrained transportation [20–22], meaning that transported goods exhibit such a high density (e.g. construction materials, liquids) that the truck's weight limit is reached before its volume limit. However, logistics research suggests that larger and increasing shares of transportation are constrained by cargo volume (e.g. refrigerators, parcels) [21,23–25], thereby relaxing the impact of weight drawbacks for BETs in particular. Both, a limited scope of technologies in available studies and their focus on weight-constrained transportation, currently impede a differentiated forecast of the market segmentation for future long-haul trucks. In the underlying study, the relative competitiveness of BETs to FCETs and DTs in long-haul transportation is evaluated by applying a cost estimation method to U.S. heavy-duty trucks that incorporates technology-specific profit deviations due to charging/fueling times and cargo capacities, and reflects weight- and volume-constrained transports. The conducted analysis differentiates between current and future state-of-technology, specific battery chemistries, energy price developments and evaluates the impact of autonomous driving on the cost-effective technology choice. The use case of full truck load transports at U.S. highways is focused and U.S. regulation regarding gross vehicle weight and length is assumed throughout the study and, for human driving regimes, compliance with drivers' hours of service [26] is maintained. For BETs, the battery is dimensioned to provide sufficient energy until the first (mandatory) break that is used for charging. The results are presented based on three scenarios distinguished by their state-of-technology, energy price levels, and vehicle automation level.

2. Literature review and overview of truck market

The technical and economic competitiveness of different truck technologies in heavy-duty and long-haul truck transportation has been the object of multiple research studies in the past decade. Relevant publications on the topic, analyzed truck types and criteria for comparison are displayed in Table 1. A brief summary of these publications is outlined in the following section.

Publication	Truck types	Criterion	Opportunity cost	Cargo focus	BET battery technology
Nykvist, B. & Olsson, O. [22]	DT, BET	Capital cost, operating cost	Charging time, Payload deficit	Weight	NMC
Wolff, S., Fries, M. & Lienkamp, M. [27]	DT, HyT, BET, FCET, CaT	Capital cost, operating cost	-	Weight	LIB
Liimatainen, H., van Vliet, O. & Aplyn, D. [28]	DT, BET	Energy consumption	-	Weight, volume	-
Sripad, S. & Viswanathan, V. [21]	DT, BET	Operating cost, vehicle price differential	-	Weight	NMC |C
Tanco, M., Cat, L. & Garat, S. [29]	DT, BET	Capital cost, operating cost	-	-	LIB
Earl, T. et al. [30]	DT, BET	Capital cost, operating cost	-	-	LCO
Mareev, I., Becker, J. & Sauer, D. [31]	DT, BET	Capital cost, operating cost	-	-	NMC
Sen, B., Ercan, T. & Tatari, O. [32]	DT, NGT, HyT, BET	Capital cost, operating cost	-	-	LIB
Sripad, S. & Viswanathan, V. [20]	DT, BET	Powertrain weight, Powertrain cost	-	Weight	LIB, beyond LIB
Zhao, H., Burke, A. & Zhu, L. [33]	DT, HyT, NGT, BET, FCET	Energy consumption, vehicle price differential	-	-	LIB

Table 1: Publications in peer-reviewed journals for heavy-duty and/or long-haul transportation analyzing the competitiveness of technologies

In 2013, Zhao et al. compare the emissions and economics of alternative powertrains for long-haul trucks by analyzing energy consumption and vehicle price differentials [33]. While all alternative powertrain concepts, including BET and FCET, are found to offer potentials for emission reduction, none of the locally CO_2-free powertrains can economically compete with DTs at the state-of-technology of the time. In their study of 2017, Sripad and Viswanathan investigate performance metrics required for BETs to achieve competitiveness with DTs [20]. The authors focus on weight-constrained heavy-duty transportation, analyze the respective energy requirements in detail, and identify the battery as the main hurdle for BETs to outperform DTs. The main challenges are shown to be its low specific energy and high cost that may only be overcome by beyond lithium-ion battery (LIB) chemistries. In the same year, Sen et al. evaluate life cycle cost and emission of CO_2 equivalents of heavy-duty truck powertrains [32]. Among various alternatives, BETs are shown to be a promising DT alternative in both aspects. However, only BETs with battery energies of up to 400 kWh are analyzed that might not be large enough for long-haul transportation. Likewise in 2017, Mareev et al. conduct a life cycle cost analysis for heavy-duty trucks in long-haul transportation in Germany and set a particular focus on BET energy consumption and battery dimensioning [31]. It is shown that for vehicle ranges greater than 500 km, battery energies of 900 kWh are required, reducing BETs' average cargo weight capacity by 20% compared to DTs. Regarding life cycle cost, BETs are shown to already reach levels similar to DTs. In 2018, Earl et al. investigate the economic competitiveness by comparing TCO between long-haul BETs and DTs in the EU [30]. It is shown that BETs may become competitive at low electricity cost levels, reduced road taxes and without the need for battery replacements. In 2019, Tanco et al. conduct a break-even analysis for long-haul BETs in Latin America by comparing their TCO to that of a DT [29]. The authors find that for heavy-duty trucks, BETs struggle to reach cost parity to DTs, mainly explained by the high initial investment, even though potential battery replacements are neglected in their analysis. In the same year, Sripad and Viswanathan quantify the economic viability of heavy-duty long-haul BETs [21]. By thoroughly analyzing the trade-off between initial truck investments and operating cost, the authors derive four targets, each of which needs to be met to allow for BET economic competitiveness. These consist of improved aerodynamics to reduce required battery energies, battery pack prices below 150 $ kWh^{-1}, electricity prices below 0.2 $ kWh^{-1}, and improved battery cycle stability. Likewise in 2019, Liimatainen et al. assess the potential of electric trucks in Switzerland and Finland by comparing the energy consumption of BETs and DTs [28]. The authors find that the electrification potential increases with, on the one hand, the state-of-technology consisting of battery size, battery specific energy and charging power and, on the other hand, with the type of commodity. Commodities that are rather constrained by cargo volume capacity exhibit higher electrification potential than those that are constrained by cargo weight capacity. In 2020, Wolff et al. evaluate the economic impact of alternative powertrains in long-haul transportation based on TCO and take infrastructure investments into account [27]. BETs are assessed to be uncompetitive in long-haul applications due to cost, range, and cargo weight capacity drawbacks, both induced by insufficiently advanced battery technology. In 2021, Nykvist and Olsson compare the cost-effectiveness of BETs and DTs in weight-constrained transportation based on different gross vehicle weights [22]. The authors find that fast charging enables the use of smaller batteries that decreases energy consumption and payload deficits, and that BET competitiveness might have been underestimated by earlier studies.

Three limitations of the analyzed studies have been identified that can be derived from Table 1. First, all studies that evaluate cost competitiveness have to date focused on weight-constrained transportation. Second, none of the analyzed studies compares the economic performance of specific battery chemistries in BETs. Third, comprehensive cost competitiveness (i.e., including opportunity cost) has so far only been evaluated between BETs and DTs, neglecting market influences from the presence of FCETs. Consequently, a differentiated market segmentation that reflects volume- and weight-constrained transportation, integrates the technological concepts of DTs, FCETs, and BETs, and for the latter, the presence of multiple battery technologies, is currently lacking.

In order to underline the necessity of such an analysis, a review of public sources such as media and company websites has been conducted that provides an overview of truck technologies currently on the market or in commercialization. A summary of results based on vehicle range, maximal gross vehicle weight of the trailer combination, and truck propulsion technology is provided in Figure 1. Further details regarding start of production and related data sources are provided in Table 2.

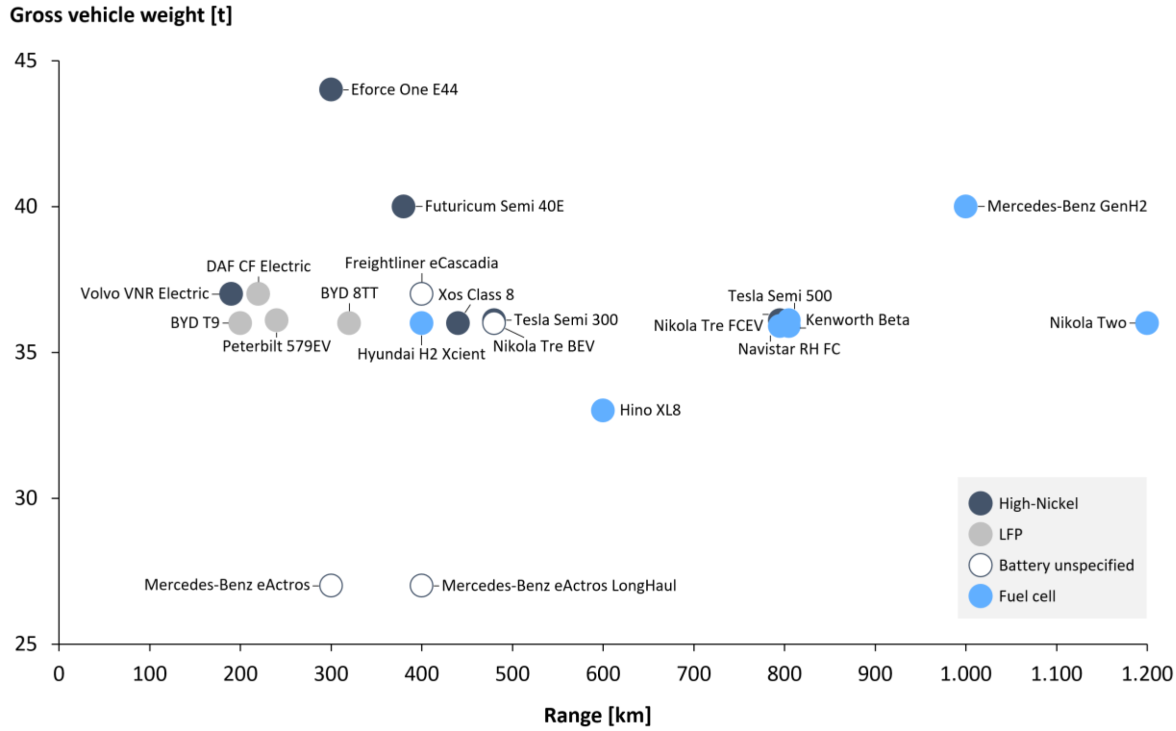

Figure 1: Summary of BETs and FCETs currently on the market or in commercialization based on vehicle range, maximal gross vehicle weight and truck propulsion technology

Manufacturer	Model	GVW	Range	Technology	(Planned) SOP	Source
Tesla Motors	Semi 300	36 t	480 km	High-Nickel	2021	[34]
Tesla Motors	Semi 500	36 t	800 km	High-Nickel	2021	[34]
BYD	T9	36 t	200 km	LFP	2020	[28,35]
BYD	8TT Gen 3	36 t	320 km	LFP	2021	[36]
Freightliner	eCascadia	37 t	400 km	Battery	2022	[37]
Mercedes-Benz	GenH2	40 t	1,000 km	Fuel cell	2027	[38,39]
Mercedes-Benz	eActros long-haul	27 t (40 t*)	400 km	Battery	2024	[40]
Mercedes-Benz	eActros	27 t (40 t*)	300 km	Battery	2021	[40]
Nikola Motors	Nikola Two	36 t	1,200 km	Fuel cell	2024	[41,42]
Nikola Motors	Nikola Tre FCEV	36 t	800 km	Fuel cell	2023	[41,42]
Nikola Motors	Nikola Tre BEV	36 t	480 km	Battery	2022	[42]
Volvo Trucks	Volvo VNR Electric	37 t	190 km	High-Nickel	2021	[43]
Hyundai	H2 Xcient	36 t	400 km	Fuel cell	2020	[44]
Eforce One	E44	44 t	300 km	High-Nickel	2019	[45]
DAF Trucks	CF Electric	37 t	220 km	LFP	2021	[46]
Futuricum	Semi 40E	40 t	380 km	High-Nickel	2019	[47,48]
Peterbilt	579EV	36 t	240 km	LFP	2021	[49,50]
Hino	XL8	33 t	600 km	Fuel cell	2021	[51,52]
Kenworth	Beta	36 t	800 km	Fuel cell	n/a	[51]
Xos Trucks	Class 8	36 t	440 km	High-Nickel	2021	[53,54]
Navistar	RH fuel cell	36 t	800 km	Fuel cell	2024	[55]

* Mercedes-Benz eActros and eActros long-haul will be available with a GVW of 40 t, related range specifications have not been available

Table 2: Manufacturer, model, gross vehicle weight, range, propulsion technology, (planned) SOP and related sources of BETs and FCETs on the market or in commercialization

It can be observed from Figure 1 that both, FCETs and BETs are in focus of truck manufacturers, the latter representing the majority of the planned model portfolio and differing in battery chemistry. In contrast to the literature, where a comparison of specific battery chemistries and an analysis of the influence from FCETs is currently lacking, the respective technologies are set to compete against each other in the truck market. In terms of vehicle range, LFP-BETs are stated to travel between 200 and 320 km, and High-Nickel-BETs between 190 and 800 km on one charge. FCETs exhibit the highest vehicle ranges that vary from 400 to 1,200 km. Hence, in order to identify the cost-effective technology choice for haulers, a comprehensive evaluation of these technologies in both, weight- and volume-constrained transports is required.

3. Methods

3.1 Cost estimation model

In order to determine the cost-effective technology choice in a specific use case, a cost estimation model is set up that addresses the aforementioned limitations and reflects weight- and volume-constrained transportation and different battery chemistries. In the following, a superordinate extract of the model structure is described, a graphical overview of the model components and their relations is presented, and the results of a review for current technological and market parameters are outlined. The detailed model description and the mathematical derivation of the opportunity cost equations are included in Section 1 of the Appendix.

For the analysis, the technology-specific distance-based cost $c_{total,x}$ (\$ km^{-1}) that is relevant to an investor in her truck purchasing decision is calculated as the sum of four elements:

$$c_{total,x} = c_{cap,x} + c_{op,x} + c'_{time,x} + c'_{cargo,x} \tag{1}$$

where $x \in \{DT;\ BET; FCET\}$ represents the technology of the truck, $c_{cap,x}$ the capital cost, $c_{op,x}$ the operating cost of the truck and $c'_{time,x}$ and $c'_{cargo,x}$ the cost of foregone profits compared to a diesel truck due to charging/refueling times and lower cargo capacity, respectively. Please note here that costs that are signified with an apostrophe represent opportunity costs and only exist at the moment of decision and vanish thereafter [56]. The capital cost $c_{cap,x}$ (\$ km^{-1}) is calculated as the distance-based linear depreciation of the total truck investment:

$$c_{cap,x} = \frac{1}{d_{life}} \cdot \left(I_{tractor} + I_{trailer} + I_{pt,x}\right) \tag{2}$$

where d_{life} (km) represents the total distance-based truck lifetime, $I_{tractor}$ (\$) and $I_{trailer}$ (\$) the investment for the tractor without powertrain and for the trailer unit, respectively, and $I_{pt,x}$ (\$) the technology-specific investment for the powertrain. The distance-based operating cost $c_{op,x}$ (\$ km^{-1}) is calculated based on:

$$c_{op,x} = c_{main,x} + c_{energy,x} \tag{5}$$

where $c_{main,x}$ (\$ km^{-1}) is the technology-specific truck maintenance cost, and $c_{energy,x}$ (\$ km^{-1}) the technology-specific cost for charging and fueling. The cost of forgone profits compared to a diesel truck due to charging/fueling times and due to differences in cargo capacity can be calculated according to equations (13) and (16), respectively:

$$c'_{time,x} = \left[w_{paid} \cdot \left(r_g \cdot K_{g,x} \cdot w_g + r_v \cdot K_{v,x} \cdot w_v\right) - c_{cap,x} - c_{op,x}\right] \cdot \left(1 - \frac{d(T)_{total,x}}{d(T)_{total,DT}}\right) \tag{13}$$

$$c'_{cargo,x} = \left[r_g \cdot \left(K_{g,x} - K_{g,DT}\right) \cdot\ w_g + r_v \cdot \left(K_{v,x} - K_{v,DT}\right) \cdot\ w_v\right] \cdot w_{paid} \tag{16}$$

where w_{paid} (%) represents the share of loaded, paid transports, r_g (\$ t^{-1} km^{-1}) the weight- and distance-based freight rate in the U.S., $K_{g,x}$ (t) the cargo weight capacity of a truck using technology x, r_v (\$ m^{-3} km^{-1}) the volume- and distance-based freight rate, $K_{v,x}$ (m^3) the cargo volume capacity of a truck using technology x, w_g (%) and w_v (%) the shares of weight- and volume-constrained transports, respectively, and $d(T)_{total,x}$ the truck's total traveled mileage in a time window T.

A graphical representation of the structure of the BET cost model is displayed in Figure 2. The overview includes model variables, model parameters, links to the DT model required for the opportunity cost calculation and references to the equations described in Section 1 of the Appendix.

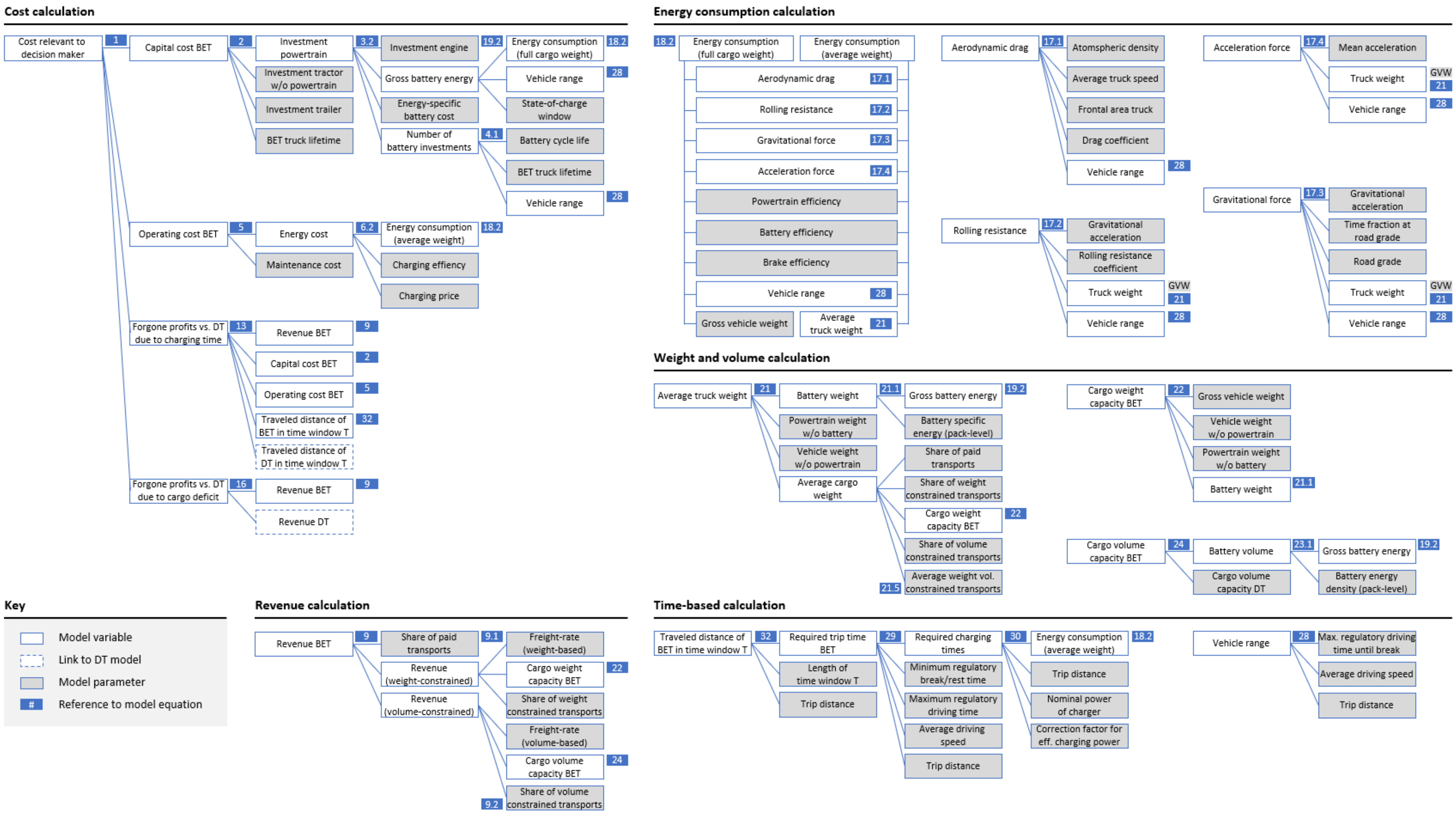

Figure 2: Graphical representation of model structure for BETs

3.2 Scenario overview and overarching assumptions

In order to analyze the effect of developments in technology, energy prices, and the level of automation on the competitiveness of truck powertrain technologies in the U.S. market, three scenarios are set up. While the first scenario is intended to reflect the current state-of technology and energy prices for electricity charging and hydrogen fueling, the second and third scenarios approximate their potential future state. Both, the first and the second scenario assume the truck to be driven by a human driver, bound to comply with break and rest time regulations, whereas in the third scenario, autonomous driving is considered. A brief overview of the three scenarios is provided in Table 3.

Scenario	**1**	**2**	**3**
State-of-technology*	**Current**	**Future**	
	Commercialized LFP	Advanced LFP	
	Commercialized High-Nickel	Advanced High-Nickel	
	Commercialized Fuel cell	Advanced Fuel cell	
	Commercialized Diesel: technological maturity is assumed throughout Scenarios 1 to 3		
Energy prices (charging/H_2 fueling)	**Current** + sensitivities	**Future optimistic** + sensitivities	**Future optimistic**
Automation level	**Human driver**		**Autonomous**
	Regulatory break time of 0.5 h after 8 h, regulatory rest time of 10 h after 11 h		No regulatory break & rest times considered
Further scenario details	Table 5	Table 6	

*State-of-technology is reflected in energy efficiency, share of useable energy, gravimetric and volumetric performance, durability, and cost

Table 3: Overview of the three considered scenarios

While assumptions specific to each of the above introduced scenarios are outlined in Section 4, several assumptions are held constant across scenarios. These are presented in Table 4 and include overarching characteristics of the truck and its components, as well as U.S. driving cycle and hours of service regulations. It should be noted here that several of these assumptions are U.S.-specific and the outlined results are expected to alter if assumptions for other countries are considered.

Parameter	Value/unit	Source
Truck life	1,609,344 km (1 million miles)	[57]
Investment tractor unit w/o powertrain	110,000 $	[58]
Investment trailer unit	32,500 $	[32]
Maintenance cost DT	0.096 $ km^{-1}	[58]
Maintenance cost BET	0.062 $ km^{-1}	[58]
Maintenance cost FCET	0.096 $ km^{-1}	[58]
Energy density of diesel fuel	9.8 kWh L^{-1}	[58]
Specific energy of hydrogen	33.3 kWh kg^{-1}	
Engine power	350 kW	[25]
Efficiency of charger	95 %	[25]
Share of empty runs	9 %	[59]
Freight rate	0.117 $ t^{-1} km^{-1}	[60]
Density of air	1.2 kg m^{-3}	
Average truck speed	19.2 m s^{-1} = 43 miles h^{-1} = 69.2 km h^{-1}	[20]
Frontal area truck	3.5 m x 2.5 m	
Drag coefficient	0.65	[61]
Rolling resistance coefficient	0.0065	[61]
Time fraction at road grade	15 %	[20]
Road grade	1 %	[20]
Mean acceleration	0.112 m s^{-2}	[20]
Brake efficiency	97 %	[20]
Battery size FCET	70 kWh	[30]
Weight truck and trailer w/o powertrain	10.8 t	[4]
Weight powertrain BET/FCET w/o battery, fuel cell, storage	0.4 t	[30]
Weight powertrain DT w/o storage	3.2 t	[4]
Correction factor charging power	0.75 (150 kW) / 0.6 (350 kW)	[62]
Regulatory minimum break time (after 8h)	0.5 h (not considered in Scenario 3)	[26]
Regulatory minimum rest time (after 11h)	10 h (not considered in Scenario 3)	[26]

Table 4: Overarching assumptions including truck characteristics, U.S. driving cycle, and break and rest time regulations

4. Scenario-based results and discussion

4.1 Scenario 1: Current technology, current energy prices, human driver

In the first scenario, trucks are equipped with propulsion technology currently available on the market. Further, current charging technology and energy prices at U.S. highways are assumed. A human driver operates the truck and needs to comply with break (≥0.5 h after 8 h driving) and rest time regulations (10 h after 11 h driving) that BETs can seize to recharge and partially offset profit disadvantages. An extract of relevant parameters is outlined in Table 5.

Category/ Parameter	LFP BET	High-Nickel BET	FCET	DT
Technology				
Energy efficiency				
Energy storage/Fuel converter	95 % [63,64],[a]	95 % [64–66],[a]	60 % [67]	46 % [30]
Powertrain	90 % [20]	90 % [20]	90 % [20]	90 % [20]
Share of useable energy				
State-of-charge window	100 % [68]	95 % [69]	-	-
Fuel utilization	-	-	100 %	100 %
Gravimetric performance				
Specific energy (battery pack)	125 Wh kg^{-1} [70]	170 Wh kg^{-1} [71]	170 Wh kg^{-1} [71]	-
Specific power (FC system)	-	-	650 W kg^{-1} [72]	-
Hydrogen storage weight	-	-	0.045 kg H_2 (kg storage)$^{-1}$ [73]	-
Cargo weight capacity (500 km)	20.7 t [b,c]	21.9 t [b,c]	24.3 t [b,c]	22.1 t [b]
Volumetric performance				
Energy density (battery pack)	190 Wh L^{-1} based on [74]	239 Wh L^{-1} based on [74]	239 Wh L^{-1} based on [74]	-
Power density (FC system)	-	-	650 W L^{-1} [72]	-
Hydrogen storage volume	-	-	0.030 kg H_2 (L storage)$^{-1}$ [73]	-
Cargo volume capacity (500 km)	109 m^3 [b]	109 m^3 [b]	110 m^3 [b]	112 m^3 [b]
Durability	3,000 cycles [64]	1,500 cycles [75]	25,000 h [76]	25,000 h [57]
Number of powertrain investments during truck life (500 km) [-]	1 [b]	2 [b]	1 [b]	1 [b]
Cost				
Battery cost (pack)	100 \$ kWh^{-1} [77]	140 \$ kWh^{-1} [77]	140 \$ kWh^{-1} [77]	-
FC cost (system)	-	-	190 \$ kW^{-1} [78]	-
Hydrogen storage cost	-	-	333 \$ (kg H_2)$^{-1}$ [73]	-
Engine cost	19 \$ kW^{-1} [21]	19 \$ kW^{-1} [21]	19 \$ kW^{-1} [21]	122 \$ kW^{-1} [21]
Charging power (nominal)	150 kW [79]	150 kW [79]	-	-
Energy market				
Electricity charging price	0.3 \$ kWh^{-1} [80]	0.3 \$ kWh^{-1} [80]	-	-
Hydrogen fueling price	-	-	13 \$ kg^{-1} [81]	-
Diesel price	-	-	-	0.85 \$ L^{-1} [82]
Energy consumption (500 km)				
Volume-constrained transportation	1.04 kWh km^{-1} [b]	1.01 kWh km^{-1} [b]	0.05 kg km^{-1} [b]	0.30 L km^{-1} [b]
Weight-constrained transportation	1.28 kWh km^{-1} [b]	1.28 kWh km^{-1} [b]	0.06 kg km^{-1} [b]	0.40 L km^{-1} [b]

a | See literature review on battery energy efficiency in Section 3 of the Appendix
b | calculated
c | Includes additional gross vehicle weight allowance for gross vehicle weight of 0.9 t (equals 2,000 lbs) according to U.S. regulation

Table 5: Literature-based assumptions for current state-of-technology and energy market prices. Additional assumptions and related sources are included in Sections 2 and 3 in the Appendix.

For BETs, battery chemistries are differentiated between lithium iron phosphate (LFP)-based and High-Nickel-based (comprising High-Nickel layered oxide cathode materials such as NCA and NMC [83]) chemistries, both of which represent state-of-the-art lithium-ion battery chemistries in heavy-duty trucks. The given technologies are characterized by distinct properties that can be categorized in energy efficiency, share of useable energy, gravimetric and volumetric performance, durability and cost [84,85]. Battery rate capability is excluded here since the use of long-haul-BETs' large batteries implies C-rates significantly below 2C even at extreme fast charging stations (see Section 3 in the Appendix). Based on the assumptions in Table 5, Figure 3 shows the resulting cost-effective alternative to DTs depending on the trip distance between starting point and destination, and the type of transportation. Regarding the latter, cargo types may vary between orders, and transports are differentiated between weight-constrained, mixed weight- and volume-constrained, and volume-constrained cargo. While volume-constrained LFP-BETs are competitive at each trip distance within a driver's daily driving time window, a different picture emerges for weight-constrained transportation. Here, with increasing trip distances, the cost-effective technology choice follows the order LFP-BETs, High-Nickel-BETs and FCETs. Further, it can be observed that gravimetrically inferior technologies improve their relative cost with increasing shares of volume-constrained transports, expressed by diagonally running borders between technologies.

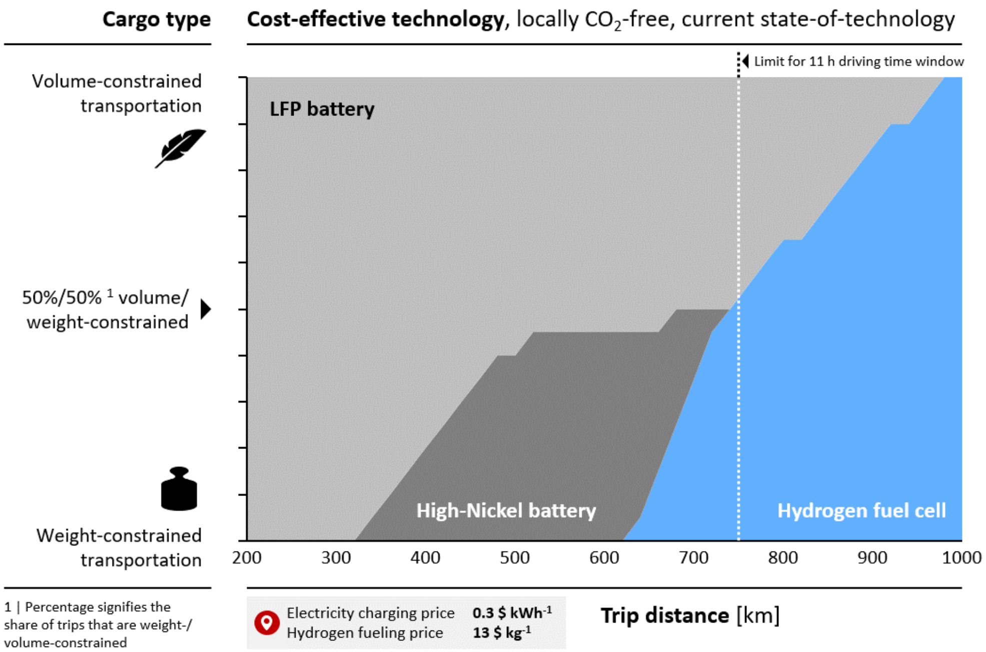

Figure 3: Cost-effective technology choice for locally CO_2-free trucks at current technology level under current U.S. regulation and energy prices

Even though Figure 3 shows defined borders between locally CO_2-free technologies, two aspects should be kept in mind during its interpretation. First, previous studies have outlined system cost [20,21,29,31] and energy prices [21,22,30,32] to be major determinants for the competitiveness of alternative powertrains (see literature review in Section 2). Since both, current system cost and current energy prices involve uncertainty, a closer look needs to be taken on the impact of different energy price levels. Second, the considered powertrains exhibit different behaviors depending on temperature conditions, affecting cost-relevant parameters such as range and durability [86,87].

Regarding the first aspect of system cost and energy price uncertainty, an impact analysis of different parameter constellations is conducted to determine the effect on the presented borders between cost-effective technologies. In order to validate the assumptions in this study, a literature review for system cost and energy prices is included in Sections 4 and 5 in the Appendix. Using the estimates for both cost drivers from multiple industry analysts, parameter constellations favoring FCETs and BETs, respectively, are applied and their effect is compared in Figure 4.

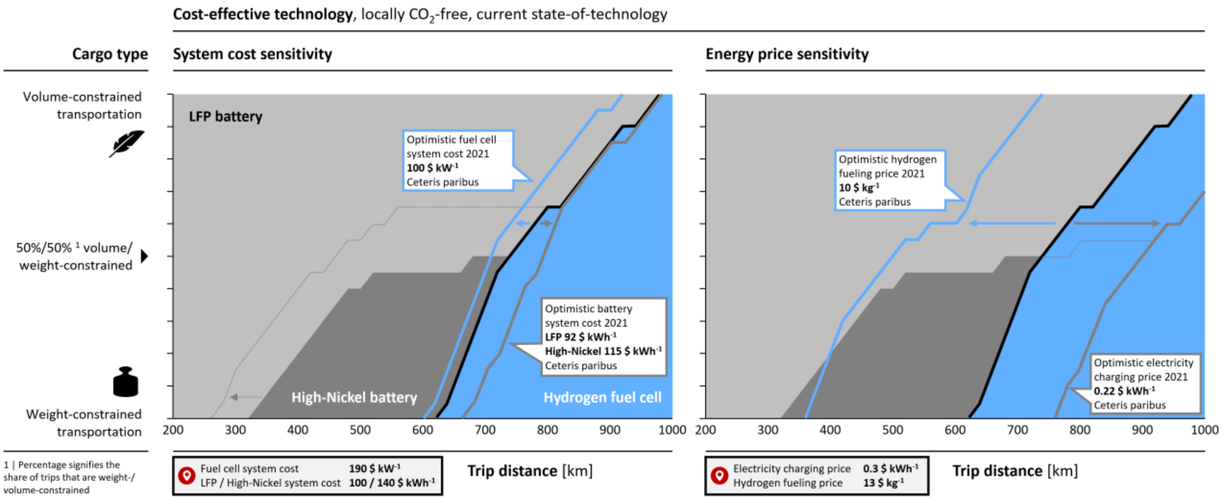

Figure 4: The effect of different system and energy cost assumptions on the cost-effectiveness of technologies at current technology level

With respect to system cost, the impact of fuel cell and battery system cost on the cost-effective technology choice is presented on the left-hand side of Figure 4. Keeping all other assumptions equal, reducing heavy-duty fuel cell system cost from 190 $ kW^{-1} [78] to an optimistic level of 100 $ kW^{-1} [88] leads to a moderate increase in FCET competitiveness at shorter trip distances, shown by a left-sided shift from the black to the blue border between FCET and BETs. Similar increases in competitiveness can be observed for BETs if optimistic LFP (High-Nickel) battery system cost of 92 $ kWh^{-1} (115 $ kWh^{-1}) [89] are assumed instead of 100 $ kWh^{-1} (140 $ kWh^{-1}) [77], shown by a right-sided shift from the black to the grey border. In both cases, additional competitiveness for the respective truck type is limited to trip distance variation of 0 to 80 km. Higher sensitivities are shown on the right-hand side of Figure 4 where the impact of energy cost assumptions is analyzed. If current hydrogen fueling is available for 10 [90] instead of 13 $ kg^{-1} [81], FCETs already become competitive at shorter trip distances (left-sided shift in the order of 200 km, blue border) if all other assumptions are kept at their original level. Reducing the level of electricity charging prices from 0.3 [80] to optimistic 0.22 $ kWh^{-1} [91,92] results in a BET competitiveness gain for additional trip distances in the order of 150 km (grey border). Consequently, an assessment of cost competitiveness between alternative powertrains needs to be developed in the context of energy price scenarios in particular. Hence, the effect of future energy price developments is further investigated in Section 4.2.

Regarding the second aspect of temperature performance, both, batteries and fuel cells face challenges at low environmental temperatures (< 0 °C) due to hampered (electro-)chemical reaction kinetics and slow ion transport [87]. With respect to batteries, the truck range is determined by their discharge energy that decreases at lower temperature levels due to overvoltages and their effect on cell capacity and cell voltage [93,94]. A similar effect applies to the durability of the battery powertrain that is defined by the rate of cell aging. Here, lower temperatures lead to an increased overpotential of the anode, bringing its potential closer to the one of lithium metal, increasing the risk of lithium plating, and thus, dendrite and electric short formation [86,87]. With respect to fuel cells, particular challenges are associated with their cold start, meaning their startup in subfreezing temperatures. In these environments, ice can form in flow channels and porous layers that can block catalyst reaction sites and gas transport pathways [95]. Cold starts have been shown to consume hydrogen [96], and hence, reduce truck range. Further, if conducted repeatedly, cold starts are considered to negatively affect fuel cell durability [97]. Consequently, both BETs and FCETs experience different performance impacts in cold climate conditions that have to our knowledge not been investigated on a comparative basis so far. Therefore, and with respect to effective countermeasures such as thermal management systems for both technologies [74,95,98], as well as advanced electrolyte additives [99–101] to improve overall kinetics in batteries, and the deployment of functional micro porous layers on the electrodes to prevent ice formation [102] for fuel cells, the cost comparison underlying Figure 3 is assumed to neither favor BETs or FCETs in particular. Further analyses provided in the remainder of this section are based on the assumptions provided in Table 5.

Figure 5 shows the cost disadvantage of BETs and FCETs compared to DTs depending on the trip distance and the type of transportation. If customers opt for locally CO_2-free transportation, it represents the minimum price premium on the distance-based freight rate that needs to be paid in order to incentivize an investor to favor BETs and FCETs over DTs under current circumstances. While locally CO_2-free transports are already competitive in weight-constrained transportation at trip distances below 300 km and investors do not need to be compensated for cost disadvantages compared to DTs, an increasing disadvantage can be observed for increasing trip distances and increasing shares of volume-constrained cargo. The first aspect can be attributed to the overproportionally increasing powertrain weights at higher trip distances of both BETs and FCETs compared to DTs. BETs need to carry larger battery weights and FCETs, despite an existing absolute powertrain weight advantage over DTs, need to carry more hydrogen, increasing weight-intensive hydrogen storage, each increasing energy consumption and, for weight-constrained cargo, decreasing profit potentials. DTs in turn benefit, owing to the high energy density of additional diesel fuel, from significantly lower marginal powertrain weight increases. The second aspect results from current U.S. regulation that grants an additional allowance on gross weight vehicle weight of 0.9 t (equals 2,000 lbs), that partially offsets the BET's weight disadvantage and increases the FCET's benefit in weight-constrained transportation. A similar allowance for additional cargo volume, such as additional truck length, currently does not exist in the U.S., lowering competitiveness of BETs and FCETs in this use case.

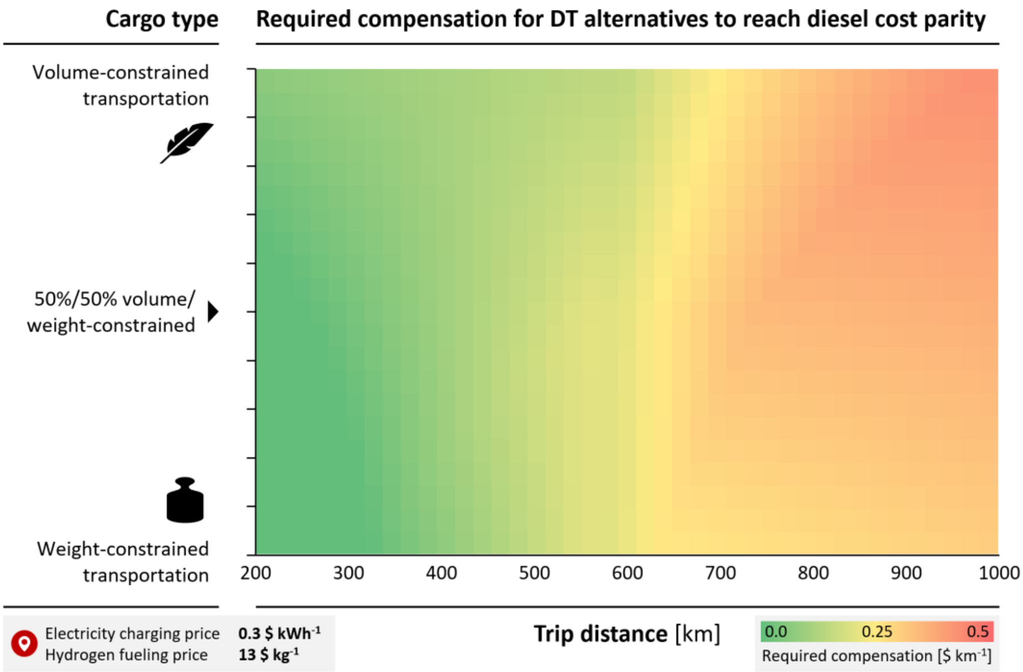

Figure 5: Required compensation for cost parity with diesel trucks, depending on trip distance and cargo type

In order to derive improvement potentials for competitiveness of locally CO_2-free trucks, the cost structure is analyzed in three suitable use cases shown in Figure 6a, where each technology reveals its cost advantage. A trip distance of 500 km is chosen for volume-constrained and weight-constrained transportation and a trip distance of 750 km in weight-constrained transportation where technology-specific cost advantages are graphically revealed (for completeness, a similar analysis for a trip distance of 200 km is included in Section 6 in the Appendix). Across use cases, the BET's efficiency-induced operating cost advantage over FCETs becomes apparent. The FCET in turn benefits from its powertrain volume and weight advantage that finds its expression in low cargo weight profit losses and cargo volume gains measured against the DT, where BETs, in both aspects, need to bear (higher) losses. With regard to the competitiveness between both BETs at 500 km, the LFP-BET is most attractive in volume-constrained transportation, where its higher battery weight from inferior specific energy (see Section 7 in the Appendix for an exhaustive analysis) only affects energy consumption, not its profit potential. This effect is overcompensated by its capital cost advantage over High-Nickel-BETs due to favorable battery durability, battery cost and share of useable energy. For weight-constrained transportation, LFP-BETs can retain this advantage only for trip distances up to 350 km (not depicted in Figure 6), since their battery weight additionally shows effect in forgone profits. For the case of 500 km, the above-mentioned trade-off tips in favor of High-Nickel-BETs. For weight-constrained transportation at a trip distance of 750 km, increased battery energies and charging times exceeding mandatory breaks, particularly driving forgone profits, render BETs uncompetitive and leave the FCET as the cost-effective alternative to DTs. Please note that in two use cases, neglecting profit deviations (signified as red, orange and green segments) alters the cost-minimal decision between DT alternatives. In all use cases, DT cost advantages become apparent. While the cost delta to DTs is in the order of 0.15 \$ km^{-1} at trip distances of 500 km, it exceeds 0.25 \$ km^{-1} for 750 km.

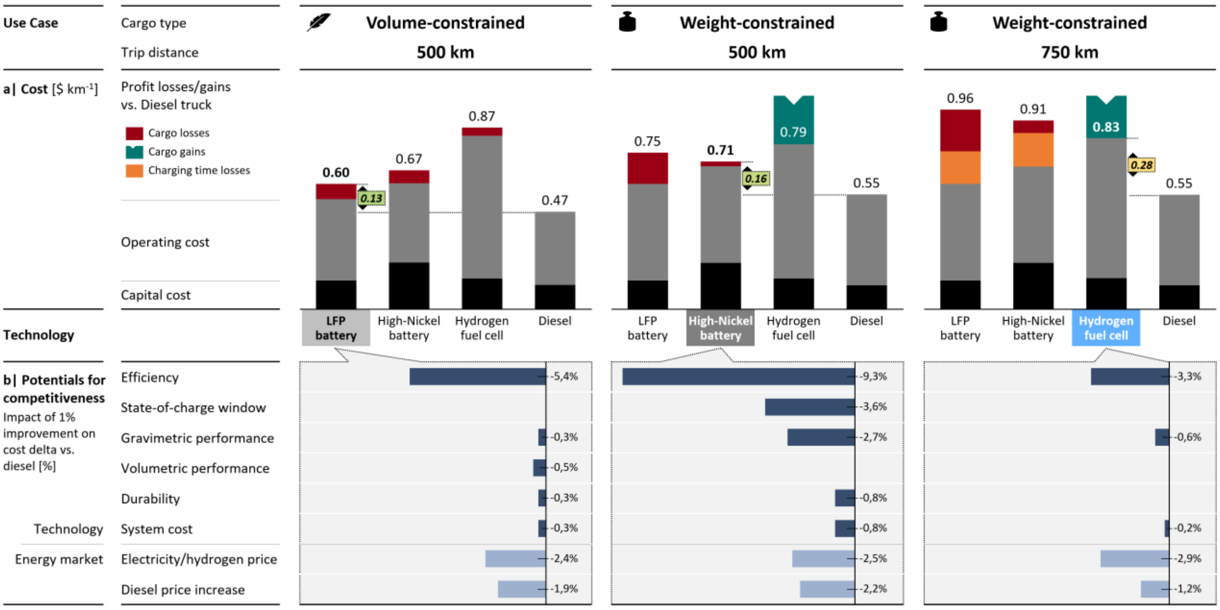

Figure 6: Cost comparison for different truck use cases and potentials to increase competitiveness versus DT

In order to identify levers for competitiveness improvement, technological and energy market parameters are varied in favor of the most competitive alternative to DTs in each use case. Parameters are varied by the same percentage (1%) and the impact on the DT cost delta is measured, as shown in Figure 6b. Of all analyzed levers, efficiency improvement proves most effective. However, its impact differs between use cases and technologies. For volume-constrained transports, the efficiency impact is generally lower compared to weight-constrained transportation due to lower average vehicle weights that drive energy consumption and cost. On FCETs in weight-constrained transportation, the impact is lower than on BETs due to the FCET's comparative weight advantage, a lower initial efficiency value

(60% vs. 95%), and a higher cost delta to DTs. The effectiveness of further technological improvements varies between alternative powertrains and requires a differentiated approach. To improve competitiveness of LFP-BETs, an increase in volumetric performance is second-most promising (subsequent to efficiency improvement), resulting in reduced penalties for forgone cargo profits. Improvements of gravimetric performance, durability and cost, play a subordinate role in comparison. High-Nickel-BETs benefit second-most from state-of-charge window improvement, thereby reducing battery cost and weight, an advantage LFP BETs cannot seize since respective packs are already assumed to withstand 100% discharge. In contrast, increasing specific energy of High-Nickel BETs proves more effective than energy density since forgone profits can thus be reduced in their more suitable weight-constrained use case. High-Nickel-BETs turn out to be slightly more sensitive to durability and battery cost due to their inferiority in both aspects. For FCETs, the second-most effective lever, again owing to their suitable use case, is gravimetric performance increase. As for BETs, system cost reductions have lower marginal impacts on their competitiveness. Regarding future powertrain R&D, this analysis reveals important implications. Even if it is taken into account that improvements may not be equally feasible in the parameters analyzed (e.g., 1% energy efficiency increase might prove more difficult than 1% cost reduction), it shows that moderate cost increases and/or compromised battery rate capability may be tolerated if these can be successfully invested in the above-mentioned technology-specific improvements. For levers related to the energy market, energy price variations significantly impact competitiveness. However, across technologies, lower energy prices for alternative powertrains are more favorable than higher diesel prices. This is due to the cost structure of FCETs and BETs, which is characterized by higher operating cost impacted by this variation. This finding has already been made in BET literature [21] but can be extended to FCETs.

4.2 Scenario 2: Future technology, energy price sensitivity, human driver

For the second scenario, a literature review is conducted on technology-specific developments based on the prioritized parameters from Section 4.1. Further, extreme fast charging technology [103] is assumed to be in place. Regarding energy market developments, the results are based on optimistic energy prices for electricity charging and hydrogen fueling (for both, see Section 5 in the Appendix), the diesel price remains constant. However, since future energy market developments involve uncertainty, the impact of different energy price scenarios on cost-effective decisions is analyzed. The assumption of a human driver is retained. Relevant parameters are outlined in Table 6, improvements compared to the first scenario are italicized and explained in the following section.

Category/ Parameter	LFP BET	High-Nickel BET	FCET	DT
Technology				
Energy efficiency				
Energy storage/Fuel converter	***97 %***	***97 %***	***70 %***	46 %
Powertrain	90 %	90 %	90 %	90 %
Share of useable energy				
State-of-charge window	100 %	***100 %***	-	-
Fuel utilization	-	-	100 %	100 %
Gravimetric performance				
Specific energy (battery pack)	***180 Wh kg^{-1}***	***240 Wh kg^{-1}***	***240 Wh kg^{-1}***	-
Specific power (FC system)	-	-	650 W kg^{-1}	-
Hydrogen storage weight	-	-	***0.065 kg H_2(kg storage)$^{-1}$***	-
Cargo weight capacity (500 km)	*22.4 t [b,c]*	*23.3 t [b,c]*	*24.7 t [b,c]*	22.1 [b]
Volumetric performance				
Energy density (battery pack)	***330 Wh L^{-1}***	***400 Wh L^{-1}***	***400 Wh L^{-1}***	-
Power density (FC system)	-	-	***800 W L^{-1}***	-
Hydrogen storage volume	-	-	***0.050 kg H_2 (L storage)$^{-1}$***	-
Cargo volume capacity (500 km)	*110 m^3 [b]*	*110 m^3 [b]*	*111 m^3 [b]*	112 m^3 [b]
Durability	***6,700 cycles***	***3,000 cycles***	***30,000 h***	25,000 h
Number of powertrain investments during truck life (500 km) [-]	1 [b]	*1* [b]	1 [b]	1 [b]
Cost				
Battery cost (pack)	***70 \$ kWh^{-1}***	***80 \$ kWh^{-1}***	***80 \$ kWh^{-1}***	-
FC cost (system)	-	-	***60 \$ kW^{-1}***	-
Hydrogen storage cost	-	-	***266 \$ (kg H_2)$^{-1}$***	-
Engine cost	19 \$ kW^{-1}	19 \$ kW^{-1}	19 \$ kW^{-1}	122 \$ kW^{-1}
Charging power (nominal)	***350 kW***	***350 kW***	-	-
Energy market (optimistic)				
Electricity charging price	***0.1 \$ kWh^{-1}***	***0.1 \$ kWh^{-1}***	-	-
Hydrogen fueling price	-	-	***4.3 \$ kg^{-1}***	-
Diesel price	-	-	-	0.85 \$ L^{-1}
Energy consumption (500 km)				
Volume-constrained transportation	*0.97 kWh km^{-1} [b]*	*0.95 kWh km^{-1} [b]*	*0.04 kg km^{-1} [b]*	0.30 L km^{-1} [b]
Weight-constrained transportation	*1.24 kWh km^{-1} [b]*	*1.24 kWh km^{-1} [b]*	*0.05 kg km^{-1} [b]*	0.40 L km^{-1} [b]

b | calculated
c | Includes additional gross vehicle weight allowance for gross vehicle weight of 0.9 t (equals 2,000 lbs) according to U.S. regulation

Table 6: Literature-based assumptions for future state-of-technology and optimistic energy market prices

Regarding BET energy efficiency improvements, the most effective lever to increase its competitiveness, increases for LFP and High-Nickel batteries can be expected in the future. A battery's energy efficiency describes the fraction of usable energy from the battery compared to the ingoing charge energy [104]. A simplified formula for the energy efficiency (η_{bat}, %) can be stated as [66]:

$$\eta_{bat} = CE \cdot VE$$

where CE represents the Coulombic efficiency (%) and VE the voltage efficiency (%), respectively. CE represents the proportion between the number of electrons returning during discharging (=discharge capacity) compared to the number stored during charging (=charge capacity). For LIBs, the number of reversible electrons is the same as the number of reversible lithium ions. Both, active lithium and electrons can be lost due to solid electrolyte interface (SEI) formation [105], various undesired side reactions at negative and positive electrodes [106], kinetic lithiation hindrances [107,108], and isolation of lithium storing electrode particles [66], leading to a loss of CE [109]. VE, on the other hand, describes the ratio of output voltage to input voltage. In practice, a gap between both can be observed that is known as overpotential and can be attributed to internal resistances during battery operation [110,111]. Strategies to increase CE include prelithiation of electrode materials [112,113], decreasing electrode surface area as in single crystal particle structures [114], particle engineering such as concentration gradient shells [115,116], and inert surface coatings [66,117]. Improvements in VE can be expected by element doping of cathode materials [118,119], the use of high-purity raw materials [120], conductive agents [121], and novel electrolyte additives [106,122]. Improvements of CE and VE both enhance a battery's overall energy efficiency as stated above.

Additional potentials for BETs in long-haul transportation may arise from the prioritized chemistry-specific improvements outlined in Section 4.1. For LFP-based batteries, limited in cell-level energy density by LFP's relatively low specific capacity and discharge voltage [123,124], major improvements can merely be expected on pack-level. Current development efforts focus on packing efficiency increases by cell-to-pack integration, rendering module elements obsolete and thus, increasing pack-level energy density [74]. Based on recently identified potentials [74], pack energy density, pack specific energy and durability are increased. For High-Nickel-based batteries, where material development faces trade-offs between energy content, power capability, durability, safety and cost [65], estimates are relied on a recently introduced Nickel-rich layered cathode material [125] that exhibits a favorable balance of the prioritized properties. By partially replacing Ni with Ta in a $Li[Ni_{0.91}Co_{0.09}]O_2$ cathode material, an increased material-level specific energy (>850 Wh kg^{-1}) is attainable compared to commercialized High-Nickel materials (~750 Wh kg^{-1} [83]) while increasing state-of-charge window and durability. Further, battery cost are expected to drop significantly [126–128] and a differentiated cost development between cell-to-pack-based LFP and High-Nickel batteries based on market expectations for 2030 [129] is assumed. For future FCETs, the achievement of the ultimate targets defined by the U.S. Department of Energy [57,72,73] is assumed.

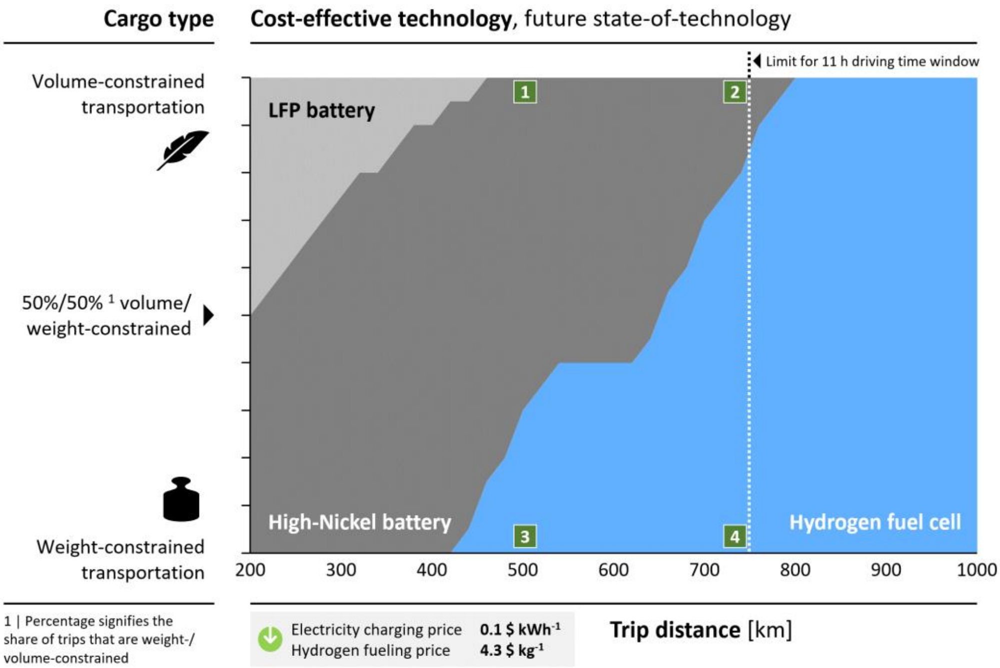

Figure 7: Cost-effective technology choice at potential future technology level under current U.S. regulation & optimistic energy prices

The resulting cost-effective technology choice is presented in Figure 7. Under this scenario, locally CO_2-free technologies are competitive to DTs in all use cases. Relative to the previous scenario, a left-sided shift can be perceived for the segmentation between BETs and FCETs, allowing FCETs to break even at trip distances 200 km shorter in comparison. This is driven by higher reductions in the FCET's operating cost that can be explained by two key points. First, even though energy prices are assumed to decrease by the same proportion (~67%) for both, charging and hydrogen fueling, the relatively higher initial level of the FCET's operating cost is affected by this reduction. Second, a higher improvement in the FCET's energy efficiency assumed, further reducing the operating cost disadvantage of FCETs compared to BETs. When comparing the border between battery chemistries, a shift in the border between High-Nickel and LFP BETs is observable. This shift in favor of High-Nickel-BETs proceeds along both dimensions, decreasing trip distances and higher shares of volume-constrained transportation. This is mainly dedicated to the High-Nickel-BET's state-of-charge window increase and its stronger cost reductions induced by durability and cost. Increases in specific energy and energy density play a minor role due to the similarity of their relative improvements. Under the given assumptions, High-Nickel-BETs will largely displace LFP-BETs in long-haul transportation and will share the long-haul truck market with FCETs. However, competitiveness is sensitive to energy price developments, rendering an exhaustive analysis indispensable. Based on the technological assumptions from Table 6, prices for electricity charging and hydrogen fueling are continuously varied and an impact analysis on the cost-effective technology choice is conducted in four cases. The results for weight- and volume-constrained transports and trip distances of 500 and 750 km, are displayed in Figure 8.

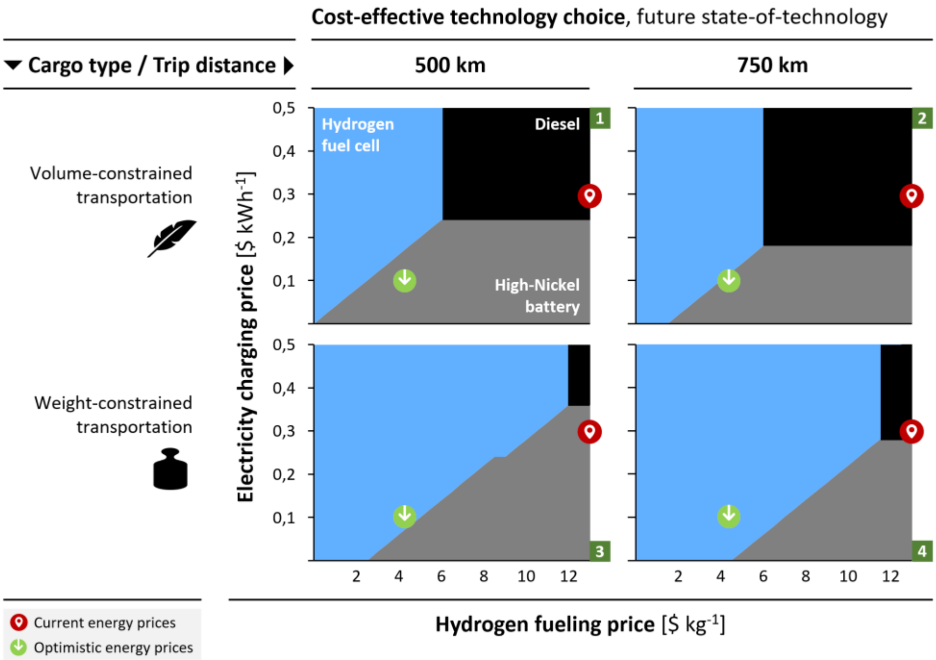

Figure 8: Impact of hydrogen fueling price and electricity charging price developments on cost-effective technology choice in different use cases

Unsurprisingly, high energy prices for alternative powertrains favor DTs in all cases and lower hydrogen fueling prices and electricity charging prices favor FCETs and High-Nickel-BETs, respectively. However, price variations do not alter the cost-effective choice between BET technologies, expressed by a lack of LFP-BET emergence in this analysis. Most strikingly, by considering the size of black segments signifying DT superiority, it can be observed that DTs are more competitive in volume-constrained transportation than in the case of weight-constrained transportation. The first reason is an extra profit opportunity for BET and FCET due to additional weight allowances (+0.9 t under U.S. regulation). The second reason is the BET's vanishing weight drawback due to increased specific energy, and the FCETs increased weight advantage. For volume-based transportation, in contrast, alternative powertrain trucks retain a volume disadvantage to DTs. Another important observation is that future alternative powertrains do not have a clear cost advantage over DTs at current energy price levels (signified by a red pin), underlining the necessity for reduced energy prices in order to decarbonize long-haul transportation. Finally, under optimistic energy price levels (signified by a green arrow), small price variations can imply shifts in the cost-optimal technology. This indicates a challenge for truck manufacturers in their technology strategy. However, cost gradients at border regimes are rather flat and may allow BETs and FCETs to coexist.

4.3 Scenario 3: Future technology, optimistic energy prices, autonomous driving

In the third scenario, results are based on the state-of-technology and optimistic energy prices from the second scenario. However, long-haul transportation is believed to be a prioritized sector captured by autonomous driving due to energy saving potentials [130], productivity improvements [131], labor cost sensitivity, potential driver shortages and traffic safety [132]. In order to assess the impact of this transition, the truck is assumed to drive autonomously and mandatory break and rest times are omitted. Hence, BETs cannot seize those for offsetting profit losses from charging. Yet, cargo needs to be unloaded and loaded between trips, still providing time windows suitable for charging. Since handling times differ between the type of goods transported [132], cargo handling times are assumed to be either 2 h and 4 h between trips. The results for both cases are displayed in Figure 9.

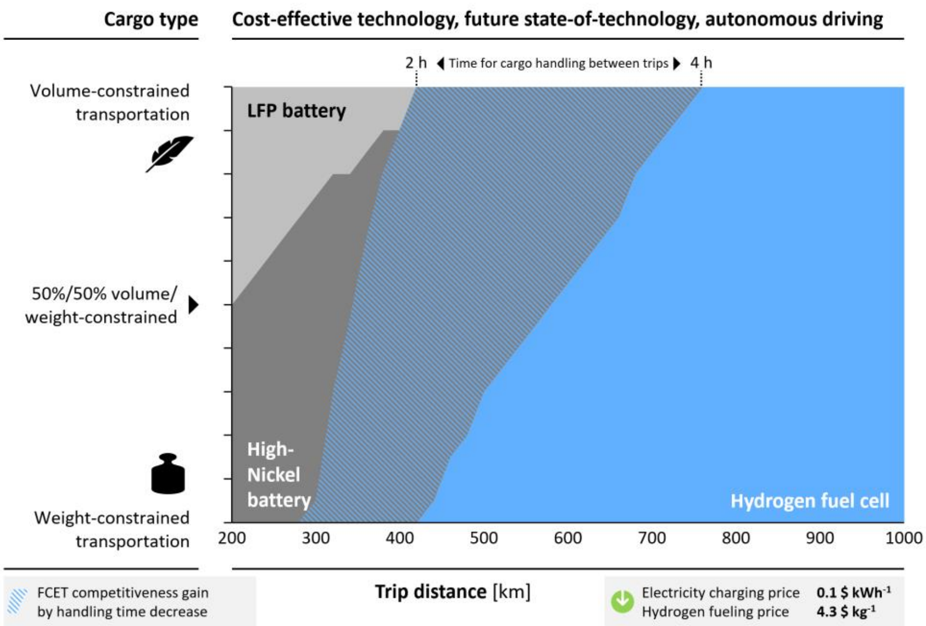

Figure 9: Impact of autonomous driving on cost-effective technology choice depending on different cargo handling times that can be used for BET charging

Compared to both previous scenarios, FCETs are cost-competitive already at shorter trip distances in both cases. This is due to the fact that BETs, without intra-trip breaks, require additional battery energy to complete longer trips, resulting in additional weight and cargo disadvantages. Further, due to significantly reduced time windows between trips, the FCET's refueling time advantage can show its full effect. Even though automated vehicles are still in an early testing and development phase [133], for completeness, an analysis of the impact of autonomous driving has been conducted for the scenario described in Section 4.1, yielding similar results for the current state-of-technology (see Section 8 in the Appendix).

5. Conclusion

The presented results show that a cost-effective technology choice in long-haul transportation is significantly impacted by the trip distance and the type of cargo carried. A new complexity that haulers and truck manufacturers are facing in their purchase and portfolio decisions, and that has been of lesser importance in a truck market dominated by a single technology. Increased consciousness and understanding of these criteria and, more extensive information exchange between market players is required for a smooth transition of the sector. The analysis for the U.S. market further showed that profit deviations can be pivotal and underlined the need for their integration in future technology decisions.

Regarding short-term competitiveness of DT alternatives, the results indicate that in the U.S., BETs are on the verge of competitiveness at shorter trip distances below 500 km. For longer trip distances, a growing compensation is required to incentivize emission elimination. Therefore, investigating customers' willingness-to-pay and developing suitable pricing models for decarbonized transports is a crucial task for industry and academia.

To increase long-term competitiveness of FCETs and BETs, R&D activities should focus on efficiency improvements. Battery R&D should further concentrate on energy density improvements for LFP-based, and on specific energy and state-of-charge window improvement for High-Nickel-based chemistries. Moderate technology cost increases for FCETs and BETs, and for the latter, compromises regarding battery rate capability may be tolerated if investments in these properties prove successful. However, at current U.S. energy prices, technological development might be insufficient for clear cost advantages over DTs and thus, policy makers and industry need to direct their attention at decreasing electricity charging and hydrogen fueling prices to support their adoption. This includes supporting the availability of affordable green electricity, capital cost reductions for electric chargers, electrolyzers and hydrogen fueling stations, and increasing the equipment utilization along the value chain in order to reduce capital cost allocation per charging or fueling event.

While FCETs, by the nature of their suitability for very long trip distances, today are furthest from competitiveness in the U.S., they currently represent the cost-effective option to decarbonize weight-constrained transportation with trip distances above 600 km. In addition, the commercialization of autonomous driving and their refueling time advantage may improve their market position considerably.

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Author contributions

Lukas Mauler: Writing - original draft & revision, Conceptualization, Methodology, Investigation, Visualization, Data curation, Software, Formal analysis. Laureen Dahrendorf: Writing – original draft & revision, Investigation. Fabian Duffner: Visualization. Martin Winter: Supervision, Validation. Jens Leker: Supervision, Project administration.

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