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A meta-study of purchase costs for zero-emission trucks

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Introduction

Heavy-duty vehicle electrification is accelerating globally as manufacturers bring an increasing diversity of zero-emission bus and truck models to market. Incentive programs, regulatory measures, and growing demand has resulted in the global sales of electric commercial vehicles increasing from roughly 5,000 to 62,000 units between 2010 and 2020 (Buysse & Sharpe, 2021).

Due to the nascent nature of the market, there is a lack of publicly available data on the costs of heavy-duty zero-emission vehicles and powertrains, especially for freight trucks. This study reviews available literature on the costs of battery-electric and hydrogen fuel cell trucks in North America and Europe in roughly the 2020 to 2030 timeframe. We focus the analysis on the heaviest freight trucks—tractor-trailers—which are responsible for roughly half of fuel consumption and greenhouse gas (GHG) emissions from the heavy-duty vehicle sector in the United States and the European Union (U.S. Environmental Protection Agency and U.S. Department of Transportation, 2016). Despite this focus on tractor trucks, the results are applicable to other truck sizes and applications, given that we present energy- and power-specific cost values.

Literature review of zero-emission truck upfront costs in the United States and the European Union

Below we present a review of the literature on the retail prices for battery-electric and hydrogen fuel cell tractor trucks. In addition, we provide information about the costs of key components for zero-emission trucks, including the battery pack, motor, and energy storage systems.

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Literature review of battery-electric and hydrogen fuel cell truck retail prices

The reported retail price of battery-electric and fuel cell trucks varies significantly depending on the use case and assumptions about individual component costs. Table 1 summarizes recent literature on the retail price of zero-emission trucks. The studies listed focus on U.S. class 8 long-haul trucks and their equivalent class 5 long-haul tractor trucks in Europe. In the North American classification system for on-road vehicles, Class 8 trucks are the heaviest category and includes trucks with a gross vehicle weight rating (GVWR) over 33,000 lb (14,969 kg). Typically, tractor-trailers operate between 40,000 lb (18,144 kg) and 80,000 lb (36,287 kg). Class 8 tractor trucks in the United States and their European equivalent class 5 long-haul trucks can also be categorized as day cab or sleeper cab. While not all studies provide information in this regard, the reported driving range can serve as an indicator, as sleeper cabs cover higher driving ranges. Tractor trucks are responsible for nearly half of the fuel use and GHG emissions from the on-road commercial vehicle sector in the United States (U.S. Environmental Protection Agency and U.S. Department of Transportation, 2016) and Europe, but are generally the most challenging heavy-duty segment to electrify due to their heavy weight and their need to often travel long distances at a time.

Table 1. Summary of the recent literature on the retail price of zero-emission trucks in 2020 and 2030.

Region	Truck class	Powertrain technology	Technical specification in 2020	Driving range	Retail price USD		Study
					2018–2020	2025/2030	
U.S.	**Class 8 tractor truck**	Battery electric	Battery: 2,200 kWh	750 miles	$816,000	$423,000 (2025)	National Renewable Energy Laboratory (Hunter et al., 2021)
		Battery electric	Battery: 1,436 kWh	500 miles	$579,000	$316,000 (2025)	
		Fuel cell	FC stack: 303 kW	750 miles	$386,000	$258,000 (2025)	
		Fuel cell	FC stack: 303 kW	500 miles	$329,000	$241,000 (2025)	
		Diesel	Engine: 317 kW	-	$165,000	$175,000 (2025)	
	Class 8 day cab	Battery electric	Not available	250 miles	$536,200	$248,200 – $398,500 (2025)	Argonne National Laboratory (Islam et al., 2020); Burnham et al., (2021)
		Fuel cell		250 miles	$312,700	$198,900 – $248,100 (2025)	
		Diesel		-	$122,300	$123,700 - $129,300 (2025)	
	Class 8 sleeper cab	Battery electric	Battery: 1,470 kWh	500 miles	$949,400	$416,400 – $693,400 (2025)	
		Fuel cell	Not available	500 miles	$359,500	$233,200 -$288,900 (2025)	
		Diesel		-	$143,500	$146,100 - $149,700 (2025)	
	Class 8 tractor truck	Battery electric	Battery: 510 kWh	180 miles	$474,900	$196,000 (2030)	California Air Resource Board (2019)
		Fuel cell	FC stack: 175 kW	180 miles	$629,100	$227,600 (2030)	
		Diesel	Engine: 350 kW	-	$134,000	$146,400 (2030)	
	Class 8 tractor truck	Battery electric	Battery: 797 kWh	375 miles	$210,600	$145,000 (2030)	Lawrence Berkeley National Laboratory (2021)
		Battery electric	Battery: 1,062 kWh	500 miles	$246,400	$159,000 (2030)	
		Diesel	Not specified	-	$125,000	Not available	
	Class 8 tractor truck	Battery electric	Battery: 2,244 kWh	300 miles	Not available	$585,000	Institute of Transportation Studies – UC Davis (Burke, 2020)
		Fuel cell	Not specified	600 miles		$249,900	
		Diesel	Engine: 300 kW	-		$134,000	
Europe	**Class 5 long haul tractor truck**	Battery electric	Battery: 1,354 kWh	600 km	€385,000	Not estimated	Noll et al. (2022)
		Fuel cell electric	FC stack: 343 kW	600 km	€330,000		
		Diesel	Engine: 343 kW	-	€150,000		
	Class 5 long haul tractor truck	Battery electric	Battery: 1,187 kWh	800 km	€417,300	€145,300 (2030)	Transport & Environment (2021)
		Fuel cell electric	FC stack: 240 kW	800 km	€391,800	€157,100 (2030)	
		Diesel	Engine: 350 kW	-	€105,500	€115,300 (2030)	

Note: Driving range is the maximum range per truck application as reported by each study. It is used as a design point to estimate the needed battery size.

The retail price of zero-emission trucks is highly sensitive to the size of the powertrain and the maximum daily driving range that the energy storage system can support. Figure 1 plots the retail prices of battery-electric trucks (BETs) and fuel cell trucks (FCETs) as function of the truck driving range based on the reported values in the literature.

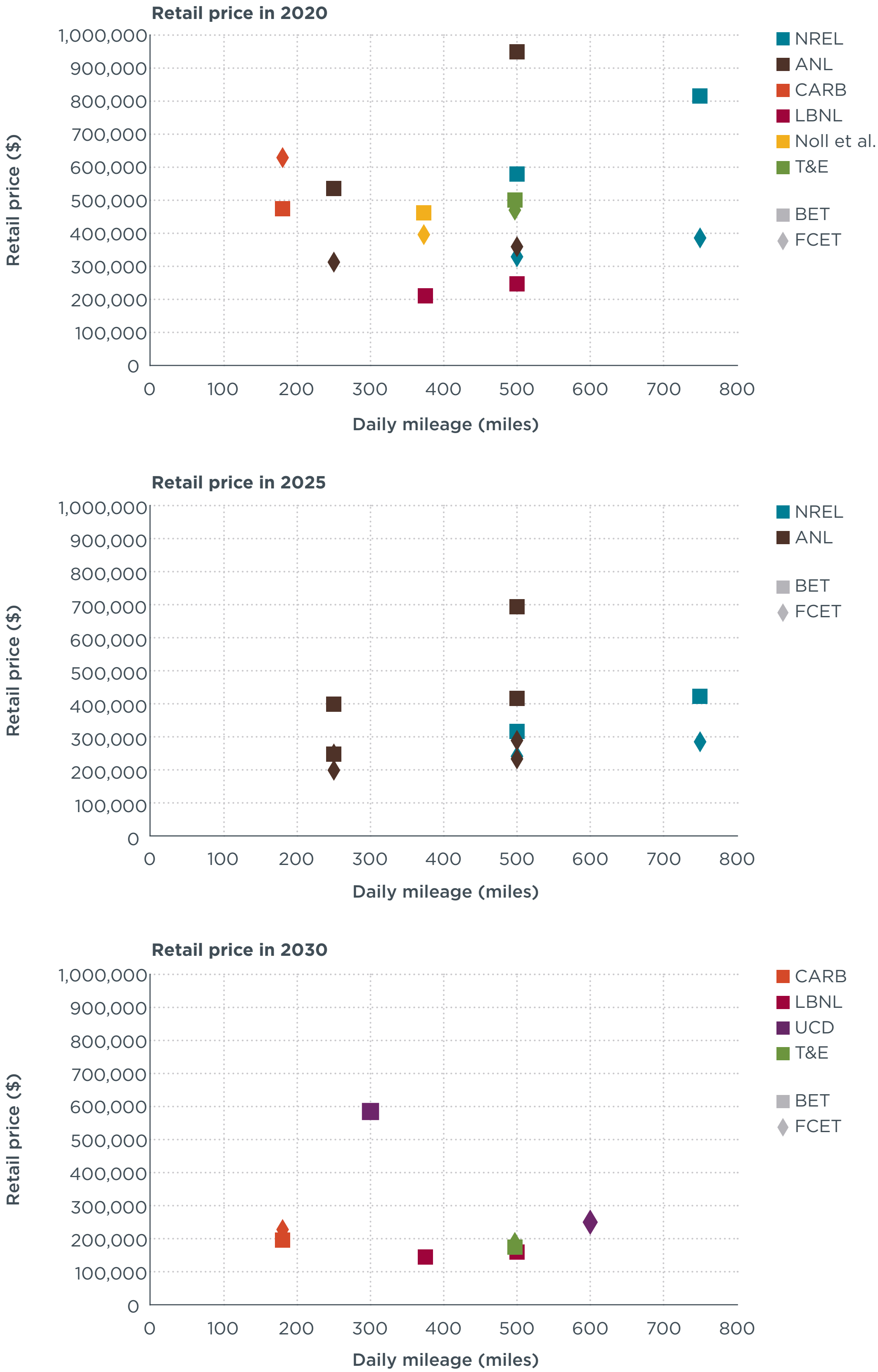

Figure 1. Battery-electric and fuel cell trucks reported retail price as function of the truck daily driving mileage. For cost data reported in Euros, we assume 1 EUR = 1.2 USD.

For battery-electric trucks, retail price is primarily a function of driving range, since higher daily energy demands require a larger battery onboard, which results in a higher battery cost and higher overall retail price, as the battery pack is the most expensive component onboard the truck. In Figure 1, this relationship is evident by looking at the studies, such as NREL, ANL, and LBNL, that estimate retail prices for battery-electric trucks with different driving ranges.

Fuel cell truck retail prices are less sensitive to driving range as shown in Figure 1. The retail price of fuel cell trucks is mainly driven by the nominal power of its fuel cell unit, which is the most expensive component onboard the truck (see cost breakdown discussion below). The fuel cell system's sizing in terms of power output is not directly related to the driving range but, rather, the truck's power demand under expected driving conditions.

Literature review of the key component costs for battery-electric and hydrogen fuel cell trucks

Figure 2 presents the direct manufacturing costs of zero-emission trucks components in 2020 and their forecasted costs in 2025 and 2030. The data are collected from the studies listed in Table 1 and the Ricardo analysis (Anculle et al., 2021). In addition, zero-emission trucks components costs were collected from Frith (2020), lithium-ion battery costs were collected from Lutsey and Nicholas (2019) and Beaty (2021), and fuel cell unit costs were collected from FCHJU and Roland Berger (2020). The data presented in Figure 2 represent the average reported costs across the considered data sources (data points and dashed lines), in addition to the minimum and maximum reported costs (bounded by the shaded area).

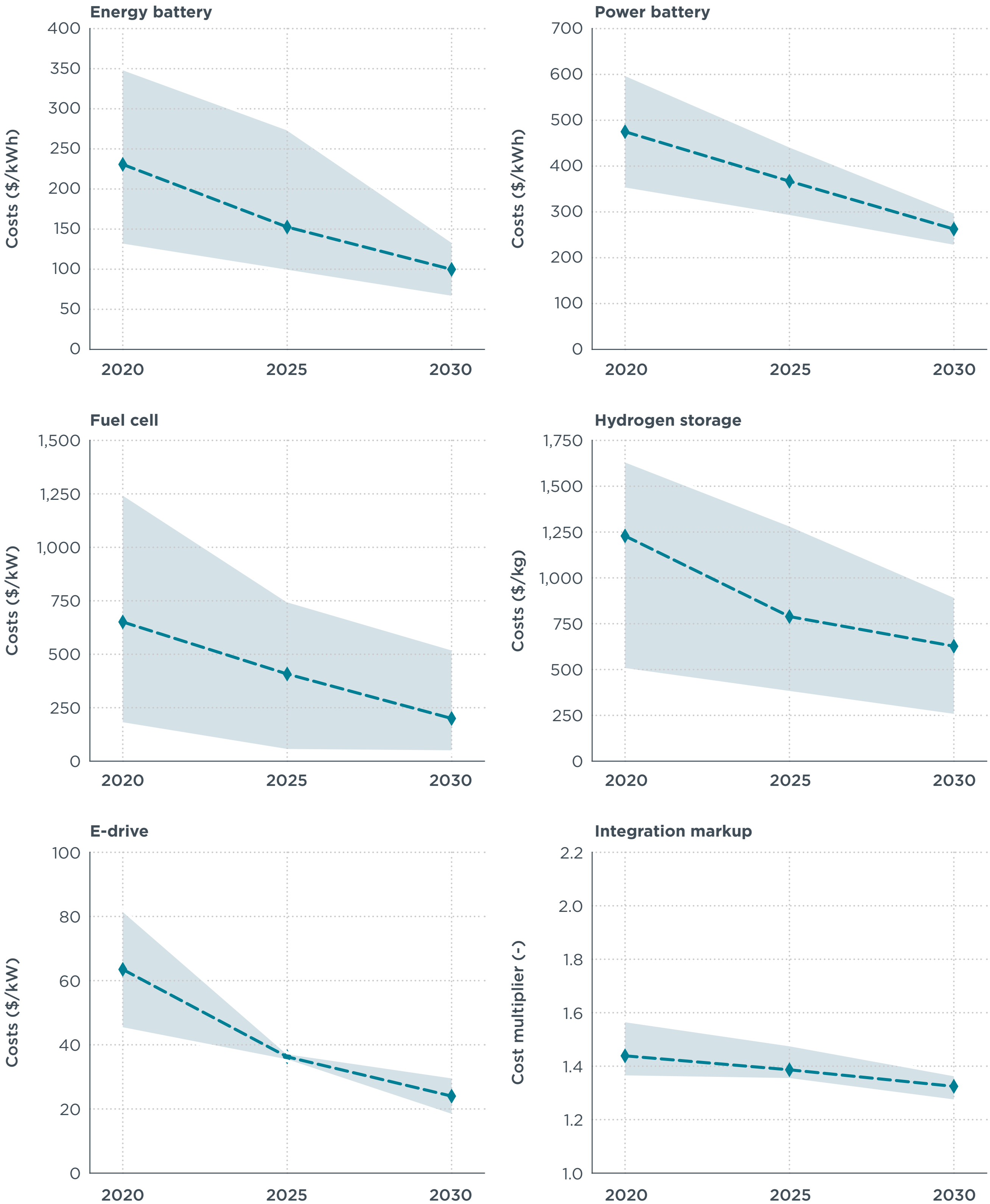

Figure 2. Zero-emission truck component direct manufacturing costs and integration markup in 2020, 2025, and 2030. For cost data reported in Euros, we assume EUR 1 = USD 1.2. Hydrogen storage cost data that are reported in $/kWh – LHV of H_2 (lower heating value of hydrogen) are converted into $/kg of H_2 assuming an LHV of 33.3 kWh/kg.

Figure 2 shows the range of cost for two types of batteries: energy batteries, which are primarily used to store energy, and power batteries, which are mainly used to provide high instantaneous power. There is always a tradeoff between the energy density and power density of the battery during its design process. Design parameters such as the current collector thickness, noble metal particle size, and coating porosity thickness determine whether a battery is energy-dense or power-dense (Lain, Brandon, & Kendrick, 2019)to investigate the internal components and cell engineering of nine cylindrical cells, with different power–energy ratios. The cells designed for high power applications used smaller particles of the active material in both the anodes and the cathodes. The cathodes for high power cells had higher porosities, but a similar trend was not observed for the anodes. In terms of cell design, the coat weights and areal capacities were lower for high power cells. The tag arrangements were the same in eight out of nine cells, with tags at each end of the anode, and one tag on the cathode. The thicknesses of the current collectors and separators were based on the best (thinnest. Battery-electric trucks are mainly equipped with energy batteries to provide the highest possible driving range, while fuel cell trucks have power batteries that are mainly used to supply additional power to the fuel cell unit during peak power demand.[1]

The top left panel of Figure 2 shows the range of costs for heavy-duty vehicle energy batteries from the literature. In 2020, the average reported energy battery cost at the pack level is around $240/kWh of nominal capacity. Transport & Environment (2021) reports the highest cost at $350/kWh, while the lowest cost is reported by Lawrence Berkeley National Laboratory (2021) at $150/kWh. Battery pack costs are expected to significantly decrease over the next decade, dropping below $150/kWh by 2025 and reaching $100/kWh by 2030. Table A1 in the Appendix summarizes the reported costs of energy batteries in the literature. The top right panel of Figure 2 shows the costs of power batteries for heavy-duty vehicle applications. As with energy batteries, the cost of power batteries is projected to drop significantly, from almost $500/kWh in 2020 to less than $300/kWh in 2030.

The reported costs of fuel cell units in 2020 show a large range, with an average cost of $500/kW. The highest reported fuel cell unit cost is reported by Ricardo (Anculle et al., 2021) at $1,250/kW, while UC Davis (Burke, 2020) reports the lowest cost at $175/kW. This disparity in fuel cell unit costs is sustained in 2030, when the average estimated cost is almost $240/kW, with a minimum price of $50/kW reported by Argonne National Laboratory (Islam et al., 2020)affordable and efficient technologies for transportation of goods and people. Translating investments in advanced transportation component technologies and powertrains to estimate vehicle-level fuel savings potential is critical for understanding DOE’s impact. In this work, we simulated technologies funded by VTO and HFTO for light duty vehicles. The simulations were performed across: Multiple powertrain configurations (i.e., conventional, power-split, extended-range electric vehicle, battery electric drive, and fuel-cell vehicles and a maximum of $500/kW reported by Ricardo (Anculle et al., 2021). This is a ten-fold difference between the minimum and maximum estimated fuel cell costs. Hydrogen storage system costs also have a similar disparity in the reported cost data. The average reported cost of hydrogen storage system is almost $1,250/kg of usable hydrogen, while reported cost in 2020 range between $500/kg (UC Davis) and $1,600/kg (Ricardo and Transport & Environment). The costs are expected to decrease by 2030, dropping to an average of

1 This is true of fuel cell trucks that primarily utilize the fuel cell for motive power. There are instances where fuel cell trucks are designed with relatively large battery packs that play a much larger role in energy storage and thus can be considered energy batteries.

$700/kg. Table A2 and Table A3 in the Appendix summarize the reported cost of fuel cell units and hydrogen storage tanks, respectively.

Another major component in a zero-emission truck is the electric drive (e-drive), composed of the electric motor, inverter, and transmission system. The average reported e-drive cost in 2020 is around $60/kw of electric motor nominal power. This is expected to drop to $25/kW by 2030.

Integration markups, sometimes referred to as indirect cost multipliers, are factors that represent costs other than the direct manufacturing costs of the component. This includes research and development, marketing, insurance, and assembly. The integration markup factor is the difference between the manufacturing cost and the price to be paid by the consumer. For heavy-duty zero-emission trucks, the integration markup factor was around 1.4 in 2020 and will drop to 1.35 by 2030 based on data provided by Ricardo and the U.S. Environmental Protection Agency (U.S. Environmental Protection Agency and U.S. Department of Transportation 2016).

In addition to the main zero-emission truck components, auxiliary components are responsible for 10% to 15% of the truck costs (see Figures 3 and 4). Ricardo's estimates of low, medium, and high costs for each of these auxiliary systems for zero-emission trucks are shown in Table 2. As shown in the two righthand columns, Ricardo's analysis assumes the costs of most of these auxiliary systems will remain unchanged taking inflation into account. The exception is the onboard charger, which is estimated to decrease by 19% and 28% in 2025 and 2030, respectively. No other source in the literature provides data on the costs of auxiliary components in zero-emission trucks.

Table 2. Summary of auxiliary components parametrized costs in zero-emission trucks as reported by Ricardo Strategic Consulting.

Component	Cost ($/kW)			Estimated cost reductions vs. 2020	
	Low	Medium	High	2025	2030
High voltage distribution system – battery electric truck a	19	27	37	0%	0%
High voltage distribution system – hydrogen fuel cell truck	19	25	32	0%	0%
Electric air brake compressor system	1,080	1,500	1,900	0%	0%
Steering pump	200	300	390	0%	0%
PTC heater	45	75	115	0%	0%
Air conditioning unit	47	70	125	0%	0%
Thermal management – battery electric truck b	17	21	27	0%	0%
Thermal management – hydrogen fuel cell truck	8	9	11	0%	0%
Onboard charger – battery electric truck	45	72	150	19%	28%
Onboard charger – hydrogen fuel cell truck	40	67	100	19%	28%

[a] The high voltage system cost is parameterized as function of the electric motor nominal power.
[b] The battery thermal management system cost is parameterized as function of the electric motor nominal power.

Cost breakdown for battery-electric and hydrogen fuel cell tractor trucks

There are a very limited number of sources that detail the breakdown of various system and subsystem costs for battery-electric and hydrogen fuel cell trucks. To address this knowledge gap, the ICCT commissioned Ricardo Strategic Consulting to conduct a "virtual teardown" analysis (Anculle et al., 2021). This analysis provides a bottom-up accounting of all vehicle costs, including the energy storage system, electric drive system, accessories, safety components, and structural elements. Ricardo also included cost estimates for manufacturing and assembly, as well as manufacturer indirect costs and profit.

As part of the analysis, Ricardo developed representative vehicle models for battery-electric and hydrogen fuel cell trucks. The comparative baseline for the battery-electric truck was a Class 8, day cab tractor truck roughly based on the Volvo VNR 300 truck. To date, all the roughly 40 battery-electric tractor truck models that have been commercialized in the United States and European Union are day cabs, such that the Ricardo baseline reflects the current market (Sharpe et al., 2020; CalStart, 2020). A Class 8 sleeper cab tractor truck was used as the comparative baseline for the fuel cell truck. While hydrogen fuel cell tractor trucks are not yet available commercially, several manufacturers are making significant investments to bring products to market over the next few years. Some key advantages for fuel cell trucks are refueling times roughly comparable to those of diesel trucks and the ability to travel further distances between refueling events. However, fuel cell trucks are inherently less energy efficient than battery electric trucks and often have higher energy costs. The specifications for each representative zero-emission truck type are summarized in Table 3.

Table 3. Key component sizes for the battery-electric and hydrogen fuel cell truck cost analysis from the Ricardo Strategic Consulting study.

	Battery-electric truck (BET)	Fuel cell truck (FCT)	Key assumptions / details
Cab type	Day cab	Sleeper cab	• Day cab: dimensions based on Volvo VNR 300 model • Sleeper: dimensions based on Volvo VNL 760 model
Approximate range (miles)	200–300	360–540	• BET: 2–3 kWh/mile (13–20 mpg diesel equivalent) energy consumption • FCT: 0.11-0.17 kg hydrogen/mile (7–10 mpg diesel equivalent)
Battery pack (kWh)	600	12	• Battery pack for BET sized to achieve higher driving range in the future
Electric drive unit (kW) Motor, inverter, transmission	350 (Continuous power)	350 (Continuous power)	• Baseline comparison engine: Volvo D13TC (455 horsepower)
Fuel cell propulsion system (kW)	N/A	390	
Hydrogen storage system (kg)	N/A	60 (Useable)	• 700 bar • Based on Toyota/Kenworth fuel cell truck specification • Packaging of hydrogen storage system behind cab

Table 4 summarizes some of the commercially available and announced battery-electric and hydrogen fuel cell tractor trucks models in North America and Europe. For battery-electric trucks, battery pack sizes range from roughly 400 kWh to 900 kWh. Ricardo's choice of the 600-kWh battery pack (Table 3) reflects their assumption that battery packs will be offered at larger sizes as battery costs decrease and energy density improves. The electric driven continuous rated power ranges between 350 kW and 500 kW. Regarding fuel cell trucks, there are limited commercially available models for this truck segment,[2] and OEMs' announcements are not clear when it comes to the truck technical specifications. The available information on the Daimler GenH2 and Hyzon

2 After initially launching the model in 2019, Hyundai revealed the 2021 XCIENT Fuel Cell heavy-duty truck in June 2021. Since being deployed to Swiss roads in October 2020, the fleet of 46 hydrogen fuel cell trucks have driven over 1 million kilometers.

Hymax 450 fuel cell truck models reveal a fuel cell unit power in the range of 240–400 kW. Ricardo's choice of a 390 kW is on the higher end of this range.

Table 4. Summary of the technical specifications of select commercially available and announced battery-electric and hydrogen fuel cell tractor trucks models in North America and Europe.

Model	Powertrain	Fuel cell power (kW)	Battery size (kWh)	E-drive power (kW)	H2 tank size and technology	Commercial availability
Freightliner eCascadia	Battery electric	-	475	373	-	Today
Volvo FH	Battery electric	-	540	490	-	Today
Kenworth T680E	Battery electric	-	396	500	-	Today
Peterbilt	Battery electric	-	396	500	-	Today
BYD TT	Battery electric	-	435	360	-	Today
Lion Electric Lion8	Battery electric	-	480	350	-	Today
IVECO-FPT-Nikola	Battery electric	-	780	480	-	2023
Futuricum Designwreck FH a	Battery electric	-	680–900	500	-	Limited supply
Nikola TRE	Battery electric	-	753	480	-	Unknown
Hyundai Xcient	Fuel cell	180	72	350	31 kg 350 bar	Today
Hyzon Hymax 450	Fuel cell	240	140	450	65 kg 350 bar	2023
Daimler - GenH2	Fuel cell	300	70	460	80 kg liquid H2	2027

[a] Volvo owns 60% of the shares of Designwreck.

Battery-electric tractor truck

Figure 3 shows Ricardo's estimated breakdown of current costs for the battery-electric tractor truck.[3] The battery pack makes up roughly 60% of the total truck cost and is over five times larger than the next most expensive component, the electric drive system, which consists of the electric motor, inverter, and transmission. The driveline, cab, and chassis account for about 9% of costs, and the remaining vehicle systems, as well as vehicle manufacturing and assembly, each represent 5% or less of total costs. Ricardo chose a battery pack size of 600 kWh, which is larger than what is generally commercially available currently. As shown in Table 4, there are several models in the market with battery sizes that are much smaller than 600 kWh, and it's likely that the battery packs for these trucks make up a smaller percentage of total costs than Ricardo's analysis.

3 Here and in the following section, we do not include the manufacturer's indirect costs or profits. As a simplifying assumption, Ricardo assigned a 36% markup (i.e., direct costs x 1.36) to both zero-emission truck types in each of the years of concern. This markup value was derived by averaging the financial information from PACCAR, Navistar, Daimler, and Volvo.

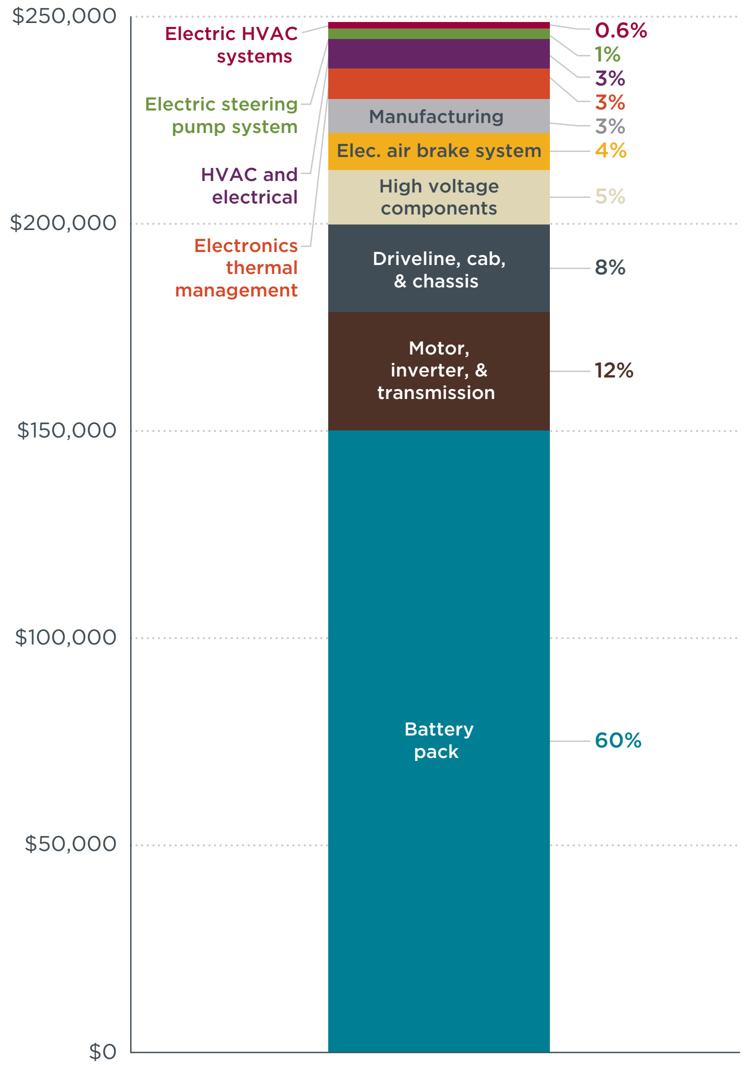

Figure 3. Estimated composition of costs for a battery-electric tractor truck in 2020. High voltage components includes the DC-DC converter, onboard charger, and high voltage distribution system.

Hydrogen fuel cell tractor truck

At present, there are no hydrogen fuel cell tractor trucks available commercially in North America or Europe. Figure 4 shows Ricardo's estimated distribution of costs for the hydrogen fuel cell truck in 2025. Estimating 2020 costs for the hydrogen truck was more challenging since these vehicles are mostly in the prototype and early demonstration phase. The 2025 values are likely more indicative of the costs in the early commercial market. The fuel cell propulsion system makes up nearly 60% of the total costs and primarily consists of the fuel cell stack and the balance of plant, which includes the air compressor, fuel loop, high-temperature loop, and sensors. The next-highest cost item is the gaseous hydrogen storage system, which includes the high-pressure (i.e., 70 MPa) carbon fiber composite hydrogen tanks, hydrogen distribution components, and the structural support elements.[4] Together, the fuel cell propulsion and hydrogen storage

4 An important limitation of the Ricardo study is that liquefied hydrogen storage was not considered. Over time as an increasing number of hydrogen fuel cell trucks are commercialized, it's likely that certain manufacturers will opt for liquefied hydrogen tanks, as these systems can often offer increased driving range and more attractive on-vehicle packaging than gaseous systems.

systems account for almost 80% of total truck costs. The driveline, cab, and chassis account for 7% of costs, and the remaining vehicle systems and manufacturing each make up 3% or less of overall costs.[5]

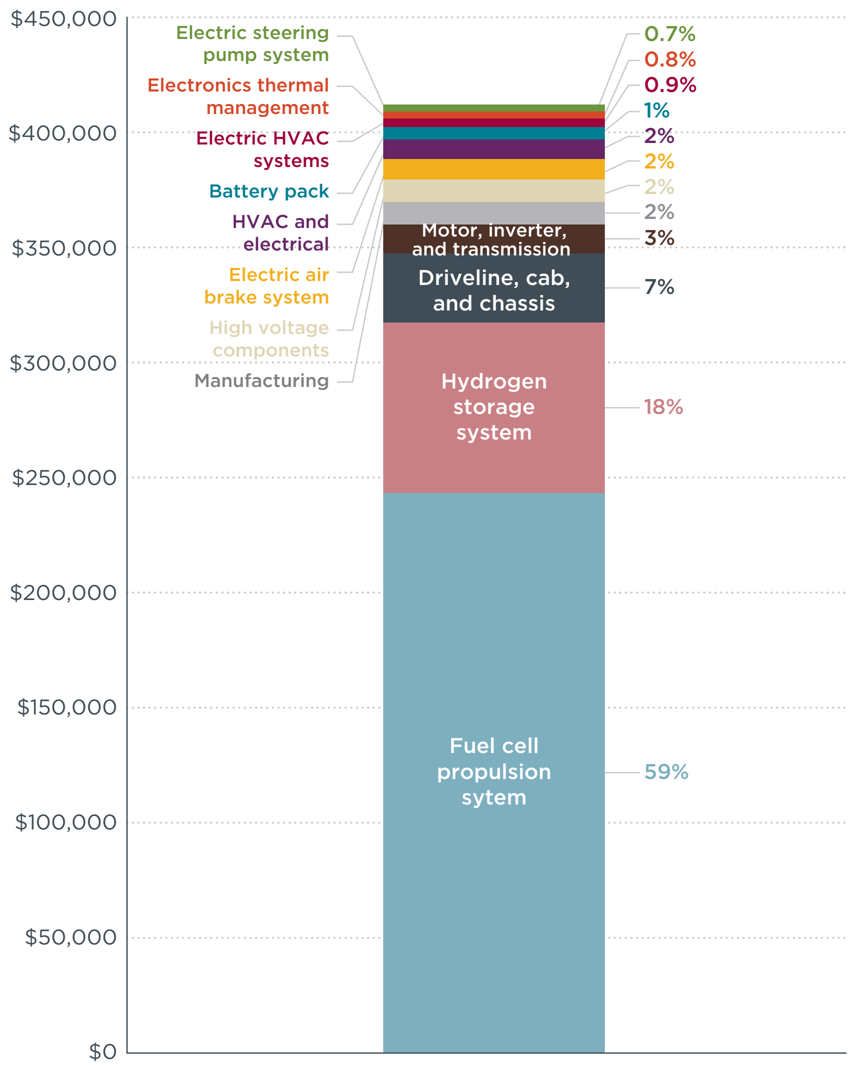

Figure 4. Estimated composition of costs for a hydrogen fuel cell tractor truck in 2025. High voltage components include the DC-DC converter, onboard charger, and high voltage distribution system.

Zero-emission truck component cost reductions

For each of the baseline vehicle models described in the previous section, Ricardo estimated component cost reductions in 2025 and 2030. In this section, we present these projected cost reductions, discuss their driving factors, and put this in context of recent literature on the expected cost reductions for key zero-emission truck components in the 2020 to 2030 timeframe.

5 For reference, in Ricardo's study, the powertrain in baseline diesel accounts for 58% (day cab) and 55% (sleeper cab) of direct costs (i.e., excluding indirect costs).

Estimated zero-emission truck component cost reductions from the Ricardo Strategic Consulting study

Battery-electric truck

Figure 5 presents the Ricardo study's estimated cost reductions in 2025 and 2030 for the battery-electric tractor truck and the breakdown of total costs in 2030. The largest share of total cost reductions come from the battery pack. Compared to 2020, costs decrease by 26% in 2025 and by 50% in 2030. Reductions in battery pack costs are attributed to continued improvement of cell and battery pack performance. Advances in battery technology include increases in energy and power density for anodes and cathodes, new and improved materials for cells, and further developments in battery packaging and integration.

The next largest contributor to overall cost reductions is the electric drive unit, which consists of the motor, inverter, and transmission. The steep declines in cost—nearly 60% by 2025 and 80% by 2030—are attributed to advanced motor architectures and integration, enhanced materials and manufacturing techniques, and higher efficiency thermal management strategies.

High voltage components, including the DC-DC converter and the on-board charger, are estimated to come down in costs by 5% in 2025 and 8% in 2030, compared to 2020. These modest cost reductions are attributed to optimization of semiconductor technology, improvements in semiconductor packaging, and improvements in design control and integration.

Altogether, costs for the battery-electric truck are estimated to decrease by 23% by 2025 and 40% by 2030 due to technological improvements and increased sales volumes. In 2025 and 2030, the reductions in battery pack costs make up about 70% to 75% of the overall projected decrease in battery-electric truck costs. Falling costs for the electric drive unit are responsible for roughly 25% to 30% of the reduction in total vehicle costs, and high voltage components account for the remaining 1% of cost reductions for the battery-electric truck.

Figure 5. Estimated cost reductions for battery-electric tractor truck components in 2025 and 2030 and the estimated composition of costs in 2030.

Hydrogen fuel cell truck

Ricardo's estimated cost reductions between 2025 and 2030 for the fuel cell truck are shown in Figure 6. The percentage decrease in costs for the battery pack and electric drive unit (i.e., the motor, inverter, and transmission) are identical to the assumed reductions for the battery-electric truck. Specific to the fuel cell truck, the cost reduction in the fuel cell propulsion system—30% in 2030 compared to 2025—is responsible for over 80% of the total decrease in costs. Performance and cost reduction measures for the fuel cell stack include reducing platinum group metals content, the use of bi-polar plates and coatings optimized for durability, and the use of an electrode and gas diffusion layer for higher connectivity. Between 2025 and 2030, the costs of the hydrogen storage system (i.e., the 700 bar tanks and the associated piping and structural components) are estimated to decline by 21%. The cost reductions in fuel storage and management are enabled by lighter weight and lower cost carbon fiber-reinforced plastic tanks and by improved pump, connectors, regulators, and nozzles. These improvements, as well as higher sales volumes of fuel cell systems for commercial vehicles globally, are estimated to yield overall cost reductions of 23% between 2025 and 2030.

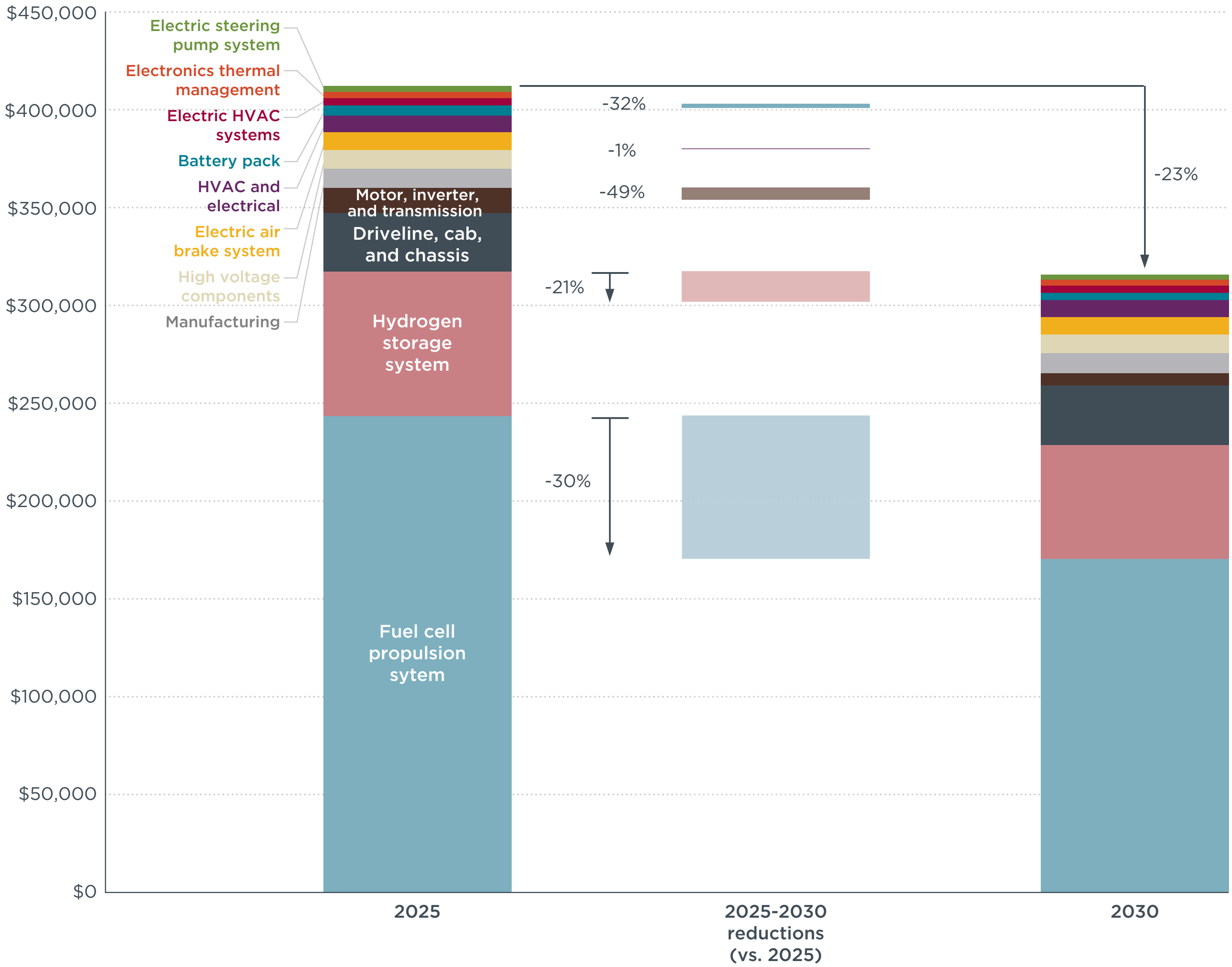

Figure 6. Estimated cost reductions for hydrogen fuel cell tractor truck components in 2030 and the estimated composition of costs in 2030.

Summary

In the early market for zero-emission trucks, there is a dearth of publicly available data about the costs of battery-electric and hydrogen fuel cell trucks, as well as cost breakdowns for the various systems in these vehicles. This study reviews recent literature on current and projected battery-electric and hydrogen fuel cell tractor truck costs.

We find that, in the literature, upfront costs for battery-electric and hydrogen fuel cell tractor trucks can vary by up to a factor of four. Battery-electric tractor truck up-front costs range from about $200,000 to $800,000, and generally costs increase with increased driving range as a function of total battery capacity (kWh). The range of fuel cell truck costs in these same studies spanned from roughly $200,000 to $600,000. At present, electric propulsion systems for zero-emission tractor trucks make up roughly 85% to 90% of total truck costs, but this is expected to fall to 75% to 85% as battery pack and fuel cell system costs are estimated to drop by 50% and 65%, respectively, over the next decade.

For battery-electric trucks, Ricardo estimates that the 600kWh battery pack makes up roughly 60% of the total vehicle cost, not including manufacturer's indirect costs and profit markup. The entire electric propulsion system, including the battery pack and the power electronics, is estimated to account for 85% percent of vehicle costs in 2020. Ricardo projects that the combined costs of the battery pack and electric drive unit would decrease by 31% and 55% in 2025 and 2030, respectively. Together, these two systems are responsible for roughly 99% percent of total vehicle cost reductions. Altogether, Ricardo estimates that battery-electric tractor truck costs will be reduced by 23% in 2025 and 40% in 2030.

For the fuel cell tractor truck, cost distribution was even more heavily weighted to the electric propulsion system. Together, the fuel cell unit and hydrogen storage system are estimated to make up nearly 80% of the total vehicle cost in 2025. Compared to battery-electric, fuel cell technology is at an even more nascent state in the trucking sector, as these truck models are not expected to become commercially available in the North American and European markets until 2023 or later. As such, the 2025 costs are a reasonable estimate for the early market for fuel cell trucks. With substantial opportunities for manufacturer learning and economies of scale, Ricardo estimates significant cost reductions in fuel cell (30% lower in 2030 compared to 2025) and hydrogen storage systems (21% lower in 2030 compared to 2025). These cost reductions, coupled with decreases in battery pack and electric drive unit costs, are estimated to result in overall vehicle cost reductions of 23% between 2025 and 2030.

We intend to closely monitor the rapidly evolving market for zero-emission trucks in North America and globally. As several of the major components for zero-emission trucks are relatively uncertain in terms of current costs and changes over time, we will update this work to reflect the most up-to-date literature, as well as the prices of commercially available zero-emission trucks as an increasing number of models are introduced in the market.

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Appendix

Table A1. Summary of reported energy battery pack costs in the literature

Energy battery cost ($/kWh)			
Study	**2020**	**2025**	**2030**
YUNEV	350	275	-
T&E	346	121	79
Ricardo	250	185	125
ANL	220	175	135
NREL	197	100	96
UC Davis	150	125	100
Noll et al.	139	-	-
LBNL	130	-	65

Table A2. Summary of reported fuel cell unit costs in the literature

Fuel cell unit cost ($/kW)			
Study	**2020**	**2025**	**2030**
Ricardo	1,250	750	525
T&E	973	371	186
FCHJU	651	370	120
Noll et al.	250	-	-
NREL	196	140	124
ANL	160 - 210	50	40 - 47
UC Davis	175	-	150

Table A3. Summary of reported hydrogen tank costs in the literature

Hydrogen storage cost ($/kg)			
Study	**2020**	**2025**	**2030**
T&E	1,640	960	880
Ricardo	1,578	1,289	900
NREL	1,200	533	480
UC Davis	500	375	250