WORKING PAPER 2023-10

MARCH 2023

Purchase costs of zero-emission trucks in the United States to meet future Phase 3 GHG standards

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Keywords: Zero-emission truck purchase costs, zero-emission propulsion systems, battery-electric trucks, hydrogen fuel cell trucks

Introduction

Heavy-duty vehicles (HDVs) are the second-largest source of greenhouse gas (GHG) emissions from transportation activities in the United States, accounting for almost 26% in 2022 (U.S. Environmental Protection Agency, 2022a). Transitioning the U.S. fleet towards zero-emission HDV (ZE-HDV) technologies is imperative for decarbonizing road transport and meeting climate goals (Miller et al., 2021). The ZE-HDV market in the United States is still in its infancy, amounting to less than 1,000 units sold in 2021, far less than the tens of thousands of ZE-HDVs sold in China and Europe (Buysse, 2022).

The upcoming revision to the HDV GHG standards in the United States provides an opportunity to set ambitious reduction targets to accelerate the transition from diesel combustion powertrains towards ZE-HDVs. This study seeks to inform the regulatory impact analysis of the upcoming rulemaking by providing updated, reliable data on the upfront cost of zero-emission trucks and buses.

This analysis revisits a previous ICCT publication on the costs of Class 8 tractor-trailers with a battery-electric or a hydrogen fuel cell powertrain in North America during the 2020 to 2030 timeframe (Sharpe & Basma, 2022). This update includes:

» The addition of new data from primary research with suppliers and industry conducted by Interact Analysis

» An adjustment for inflation to reflect 2022 U.S. dollars

» The extension of cost estimates to 2040

» New estimates of complete ZE-HDV costs for U.S. segments

The paper is divided into four sections. First, we outline the approach used for data collection and the cost methodology. Next, we present a short technology discussion and updated ICCT estimates of the cost for batteries, fuel cells, hydrogen tanks,

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electric drives, and other components. In the third section, we present estimates of the complete ZE-HDV costs for several segments for selected vehicle specifications. A summary of the findings closes the paper, followed by an appendix containing all the data from this analysis.

Methodology

Data sources

Information on the costs of critical components for zero-emission trucks, including the battery pack, motor, and energy storage systems, was collected from various data sources, listed in Table 1. These include publicly available estimates in the literature, a proprietary dataset purchased from Interact Analysis, and a Ricardo Strategic Consulting assessment carried out under contract with the ICCT.

Table 1. Main data sources used for ZE-HDV costs

Institution	Data remarks	Components included	Reference
Ricardo Strategic Consulting	• Primary data • Data specific for ZE-HDVs in the United States • Proprietary internal cost databases, supplier quotes, interviews with industry stakeholders, and public domain information	• Energy battery • Power battery • Fuel cell • Hydrogen storage • Inverter • Transmission • Electric motor	Ricardo Strategic Consulting (2021)
Interact Analysis	• Primary data • About 80% of the data is from primary research and interviews with industry experts and component suppliers • Remaining data from secondary research on public domain information.	• Energy battery • Power battery • Motor • Inverter • Transmission • Fuel cell • Hydrogen storage	Interact Analysis (2022)
ICCT	• Cost estimates of zero-emission cars in the United States • Battery pack cost estimates resulting from a weighting of 13 different data sources	• Battery packs	Slowik et al. (2022)
National Renewable Energy Laboratory (NREL)	• Estimates for U.S. ZE-HDVs from FASTSim model, which outputs vehicle total upfront costs • Powertrain costs reflect the purchase cost of components, which are multiplied by 1.5 to account for OEM markup	• Energy battery • Fuel cell • Hydrogen storage	Hunter et al. (2021)
Argonne National Laboratory (ANL)	• Prices for U.S. ZE-HDVs estimated using a cost model from Ricardo and inputs from experts from industry, Argonne, and U.S. Department of Energy	• Energy battery • fuel cell	Burnham et al. (2021)
Roland Berger	• Estimates developed with the Fuel Cells and Hydrogen Joint Undertaking	• Fuel cell	Roland Berger (2020)
Swiss Federal Institute of Technology Zurich	• Cost data derived from primary sources, with cross-referencing against secondary sources, market available data, and expert interviews	• Energy battery • Fuel cell	Noll et al. (2021)
University of California, Davis	• Own estimates supported by literature review	• Energy battery • Power battery • Fuel cell • Hydrogen storage • Motor • Inverter • Transmission	Burke & Sinha, (2020)
YUNEV	• Own estimates supported by literature review	• Energy battery	YUNEV, (2021)
Lawrence Berkeley National Laboratory	• Literature review	• Energy battery	Phadke et al., (2021)
Transport & Environment	• Own estimates based on literature review	• Energy battery • Fuel cells • Hydrogen storage	Transport & Environment, (2021)

Learning rates

Learning rates aim to forecast reductions in the cost of technology as it moves from the early commercialization phase to a mature market. The reductions in direct manufacturing costs (DMC) are attributed to learning-by-doing effects and to the economies of scale that arise as production volumes increase.

This study uses the learning curves developed by the U.S. Environmental Protection Agency for the regulatory impact analysis for the Phase 2 GHG rule for trucks and buses. These curves are shown in Figure 1 (U.S. Environmental Protection Agency & U.S. Department of Transportation, 2016). The learning curves apply to different vehicle components depending on the technology maturity at the start year of the analysis.

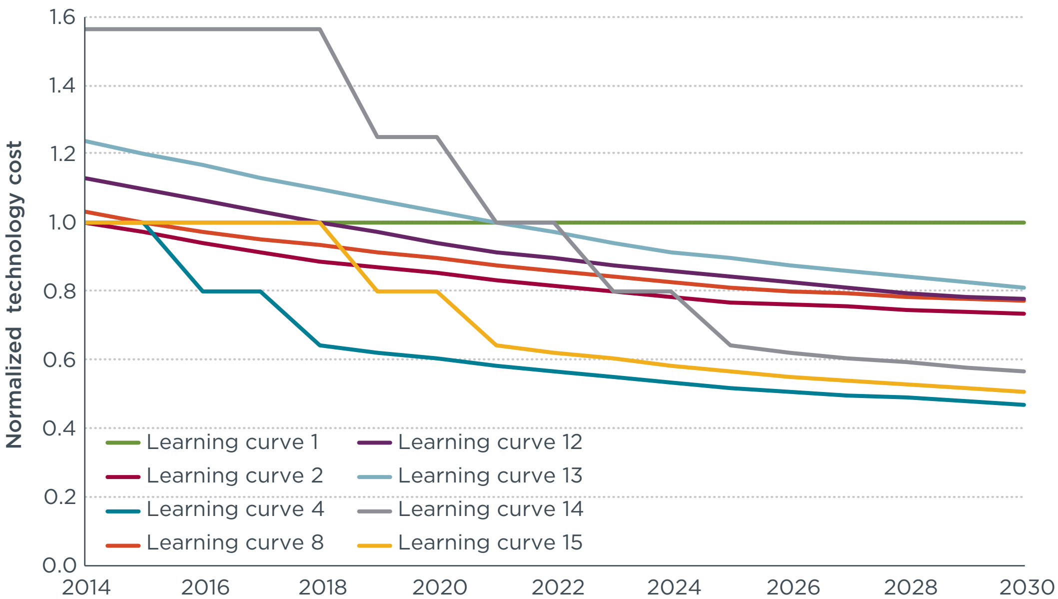

Figure 1. U.S. Environmental Protection Agency learning curves for technology cost reductions

The data sources summarized in Table 1 include forecasts of technology costs out to 2030. Thus, the learning effects must not be corrected exogenously. Cost estimates post-2030, however, are calculated using learning curves, assuming that ZE-HDV technologies have reached a mature market stage by 2030 (i.e., the flatter part of the curves shown in Figure 1). In this mature technology phase, Environmental Protection Agency curves estimate similar learning over a 10-year period, amounting to a 20% cost reduction (i.e., Learning curve 2). This improvement factor is used uniformly across all data sources to produce post-2030 technology cost estimates.

Indirect cost multipliers

Indirect cost multipliers (ICMs) account for additional expenses, such as research and development, overhead, marketing and distribution, and warranty expenditures, as well as for-profit markups. The ICMs used in this study also stem from the regulatory impact analysis for the Phase 2 GHG rule for trucks and buses in the United States (U.S. Environmental Protection Agency & U.S. Department of Transportation, 2016). To account for the nascent nature of ZE-HDV technologies, we used the ICMs corresponding to the highest complexity category (High 2). For components unrelated to the electric powertrains, such as the chassis and cabin, we used the ICM corresponding to a lower complexity category (High 1). The ICMs used are shown in Table 2.

Table 2. Indirect cost multipliers for technologies with a high technology complexity level

Complexity level	Components	Indirect cost multipliers	2020	2030
High 1	Base glider (chassis, cabin, battery packs, electric drive)	Warranty costs	0.073	0.037
		Non-warranty costs	0.352	0.233
		Total	0.425	0.270
High 2	Electric powertrain (fuel cells, hydrogen storage)	Warranty costs	0.084	0.056
		Non-warranty costs	0.486	0.312
		Total	0.570	0.368

Retail price estimation for complete ZE-HDVs

We estimate the retail prices for the different truck and bus classes using the bottom-up approach outlined in Figure 2. This approach considers the technical specifications of a representative diesel vehicle in each segment to estimate the retail price of comparable vehicles with battery electric and fuel cell powertrains. It estimates the direct manufacturing costs for each component, or group of components, individually. Retail prices of ZE-HDVs are derived using Equation 1:

$$\text{Retail price} = \text{Direct manufacturing cost} \times (1 + \text{ICM}) \qquad \text{(Equation 1)}$$

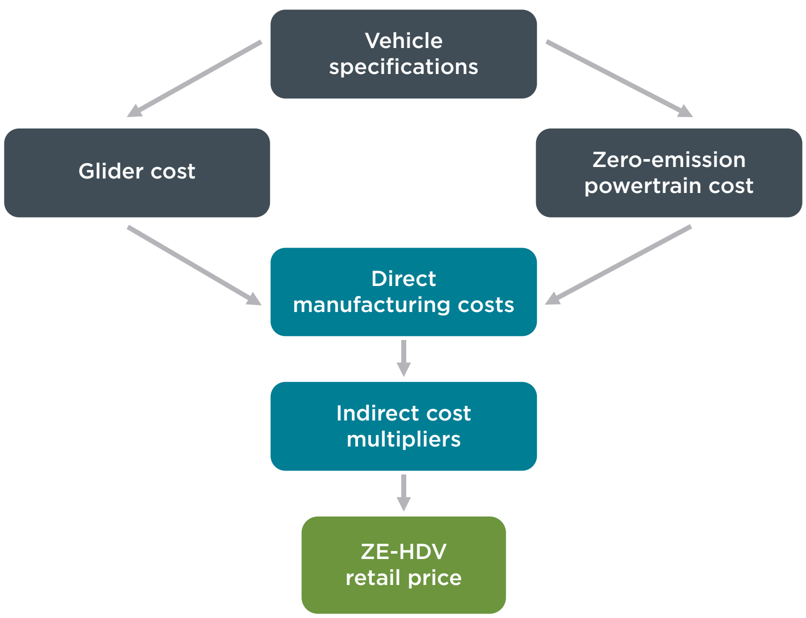

Figure 2. Approach used to estimate ZE-HDV retail prices

We developed estimates for the direct manufacturing costs of the individual powertrain components—such as the battery, fuel cell, hydrogen tank, electric drive, and electric auxiliaries—that can be scaled based on the component specifications. These estimates are summarized in the next section.

The glider manufacturing costs are estimated by subtracting the DMC of the diesel powertrain from the manufacturing costs of current HDVs. The diesel powertrain DMCs are calculated from the teardown assessment conducted by Ricardo for the ICCT (Ricardo Strategic Consulting, 2021). The manufacturing costs of HDV models from the early 2020s are estimated by dividing the retail prices publicly available in the literature by the respective ICM. The retail prices used are the average of those reported by Argonne National Laboratory (2021), Burke and Sinha (2020), Burnham et al. (2021), California Air Resources Board (2022), Hunter et al. (2021) Nair et al. (2022), and Welch et al. (2020).

We define the technical specifications of the vehicles based on the currently available commercial zero-emission HDVs in the United States. We size the battery and hydrogen tanks considering the vehicle's energy efficiency or fuel economy and the average daily mileage of a representative use case. The energy efficiency and fuel economy values are estimated by averaging the values reported by Burnham et al. (2021), California Air Resources Board (2022), and Hunter et al. (2021). The vehicle average daily mileage data is extracted from MOVES3 for each HDV segment (U.S. Environmental Protection Agency, 2022b).

Unless specified otherwise, all currency values in this paper are in 2022 U.S. dollars.

Description and costing of ZE powertrain technologies

Batteries

The cost of battery packs for ZE-HDVs can vary greatly depending on a variety of factors. These include the cell chemistry, capacity, energy, and volumetric density; lifetime requirements; charge and discharge power; manufacturer; and the buyer's purchasing leverage.

Lithium nickel manganese cobalt oxide (NMC)—with different ratios of the active cathode materials—and lithium iron phosphate (LFP) are widely used Li-ion cathode chemistries for electric vehicle batteries. Globally, LFP is the most common technology for ZE-HDVs, due to the dominance of the Chinese market; 95% of ZE-HDVs in 2021 in China carried LFP battery packs (Mao et al., 2023). However, due to the confidentiality around technology choices for upcoming products, it was not possible to assess which battery chemistry ZE-HDVs in the United States will predominantly employ. Thus, the cost estimates in this paper do not differentiate between battery chemistries.

Following this chemistry-agnostic approach, a recent ICCT study for light-duty vehicles (LDVs) in the United States estimates that pack-level costs will decline from $131/kWh in 2022 to $105/kWh in 2025, $74/kWh in 2030, and $63/kWh in 2035 (in 2020 dollars) (Slowik et al., 2022). While battery pack prices rose in 2022 for the first time since BloombergNEF (BNEF) began tracking the market in 2010, BNEF analysts predict prices to fall below $100/kWh by 2026 as the extraction of raw materials expands, the manufacturing process improves, and capacity grows across the supply chain (BNEF, 2022).

Battery costs are higher for ZE-HDVs than those of LDVs due to several technological, economic, and structural reasons, listed below (YUNEV, 2021). As a result, it will take longer for ZE-HDV batteries to reach the cost levels currently observed for LDVs and their related forecast.

» Higher energy density requirements to prevent payload loss

» Longer durability requirements to serve the high annual mileages of HDVs

» Harsher operating conditions, such as more extreme ambient temperatures and reduced vibration dampening

» Lower production volumes and worse economies of scale

» Lack of access to cells at low cost due to lower volumes

» Lack of vertical integration of battery manufacturing

» Higher non-recurring engineering costs—e.g., research and development, prototyping, validation, testing, and retooling—to integrate batteries into ZE-HDV powertrains

» Higher product specification diversity with lower manufacturing volumes

In this study, we model two different types of batteries: power and energy batteries. Power batteries, such as those observed in hybrid and fuel-cell powertrains, are used for short-term high-power purposes, and are optimized to have a high charge and discharge rate. Energy batteries are designed to store a higher amount of energy and are optimized for low rates of charge and discharge for battery-electric vehicles.

Figure 3 shows estimates for the cost of energy batteries from 2020 to 2040, based on the data collected by Ricardo Strategic Consulting (2021) and Interact Analysis (2022) from primary research, as well as data collected by Slowik et al. (2022), Burnham et al. (2021), Hunter et al. (2021), Burke and Sinha (2020), YUNEV (2021), Noll et al. (2021), and Phadke et al. (2021) from secondary research. Primary research is weighted twice as highly as secondary research to develop the ICCT cost curve.

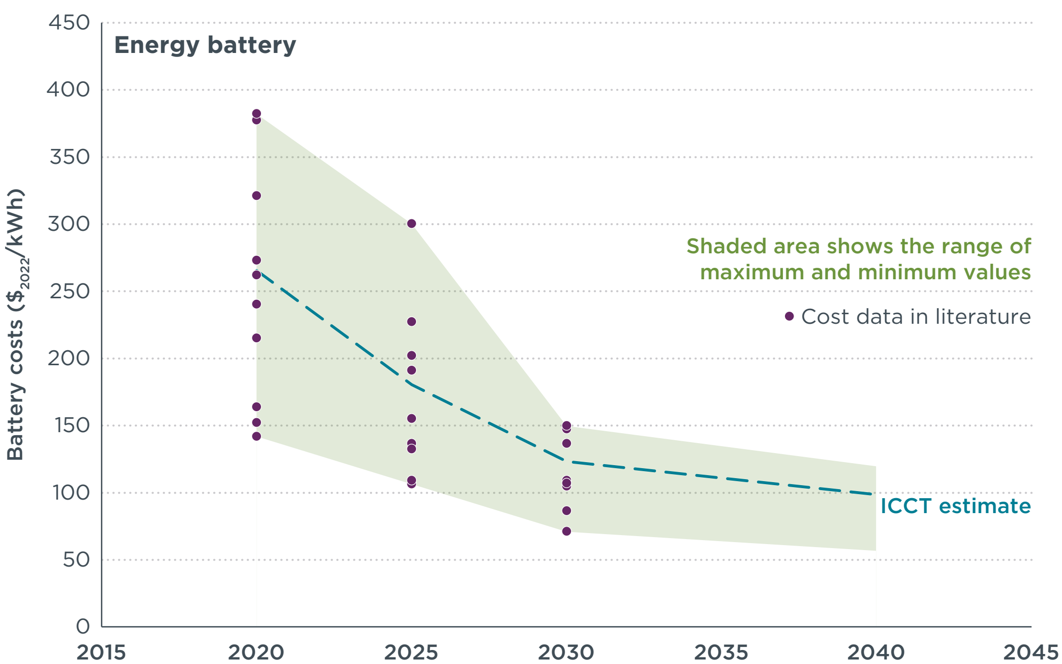

Figure 3. Estimates for the direct manufacturing cost of energy batteries

In 2020, the average reported energy battery cost at the pack level from published studies is around $265/kWh at 2022 price levels. The highest cost is reported by YUNEV (2021) at $382/kWh, while Phadke et al. (2021) reports the lowest cost at $142/kWh. By 2040, we estimate that the unit cost of energy batteries will decrease nearly two-thirds to $97/kWh.

There are fewer data points on the cost of power batteries. Figure 4 shows ICCT estimates for the cost of energy batteries from 2020 to 2040, based on the data collected by Burke and Sinha (2020), Ricardo Strategic Consulting (2021), and Interact Analysis (2022). The average cost for power batteries is $447/kWh in 2020 and will decrease by 57% to $194/kWh by 2040.

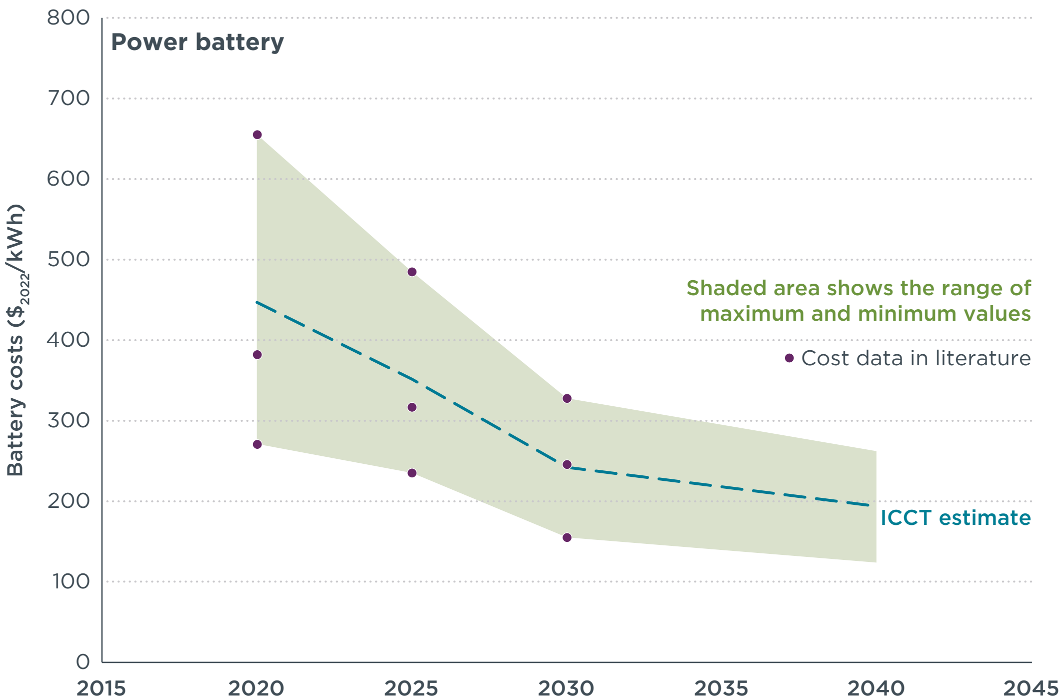

Figure 4. Estimates for the direct manufacturing cost of power batteries.

The data presented in Figure 3 and Figure 4 from 2027 to 2036 are summarized in Table 3 below, in three-year increments.

Table 3. Summary of collected data and ICCT estimates for the unit cost of batteries

Energy battery unit cost ($/kWh)				
	2027	**2030**	**2033**	**2036**
Minimum	92	71	67	62
Maximum	240	150	141	132
ICCT estimate	158	123	116	108

Power battery unit cost ($/kWh)				
	2027	**2030**	**2033**	**2036**
Minimum	203	155	146	136
Maximum	422	328	308	288
ICCT estimate	308	242	228	213

Hydrogen fuel cell

A fuel cell system is comprised of two main subsystems: a fuel cell stack and a balance of plant. The fuel cell stack, made up of fuel cell units, is responsible for generating electric power, and the balance of plant ensures the proper management of the inputs and outputs of the fuel cell stack.

Hydrogen fuel cells carry a high price tag because the components and materials most suited for vehicular applications are costly. The most common type of fuel cell in transportation is called a polymer electrolyte membrane. Among different electrolyte membranes, Nafion (i.e., perfluoro sulfonic acid electrolyte) is the most common technology for vehicular applications because of its superior conductivity, durability, and chemical stability. However, the fabrication of Nafion is expensive. Similarly, platinum is most common in the cathode catalytic layer because it excels in catalytic activity and stability but is expensive and scarce. A detailed exposition of hydrogen fuel cell systems for HDVs can be found in Basma and Rodríguez (2022).

Figure 5 shows the range of costs of hydrogen fuel cell units from 2020 to 2040, with the dashed line being ICCT's estimate. The latter is based on the primary research data collected by Roland Berger (2020), Ricardo Strategic Consulting (2021), and Interact Analysis (2022), as well as data from Burnham et al. (2021), Hunter et al. (2021), Burke and Sinha (2020), and Noll et al. (2021). Primary research is weighted twice as highly as secondary research to develop the ICCT cost curve.

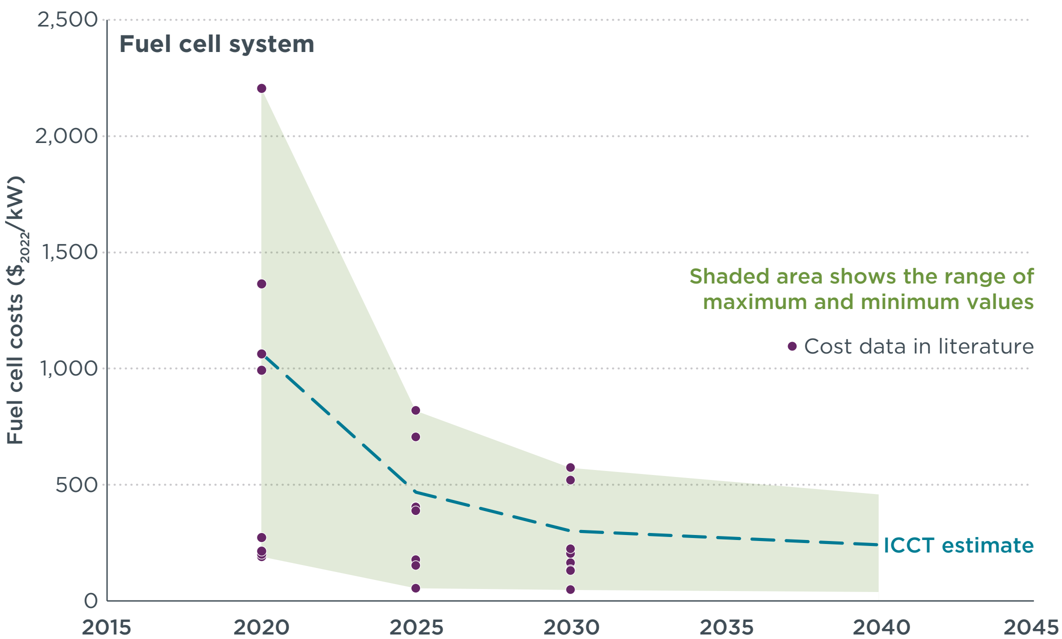

Figure 5. Estimates for the direct manufacturing cost of fuel cell systems

Roland Berger (2020) reports the highest fuel unit cost in 2020 at $2,200/kW, more than an order of magnitude higher than the lowest cost reported by Burke and Sinha (2020) at $190/kW. This high variability in the reported fuel cell unit costs is sustained in 2030, with a minimum price of about $50/kW reported by Burnham et al. (2021) and the highest reported cost of above $500/kW reported by Ricardo Strategic Consulting (2021) and Interact Analysis (2022).

ICCT's estimates, as well as the range of values found in the data, is shown in Table 4.

Table 4. Summary of collected data and ICCT estimates for the unit cost of fuel cell systems

Hydrogen fuel cell unit cost ($/kW)				
	2027	**2030**	**2033**	**2036**
Minimum	52	48	45	42
Maximum	721	573	539	505
ICCT estimate	402	301	283	265

Hydrogen fuel tank

The onboard hydrogen storage system is integral to fuel cell vehicles. The most common hydrogen storage option for vehicular applications is compressed gas at 350 or 700 bar pressure. Compressed H_2 gas at 350 bar is a standard storage technology for fuel cell buses. However, the low volumetric density of H_2 at 350 bar and the packaging restrictions for trucks results in a realistic driving range of less than 250 miles under such a configuration for class 8 long-haul trucks, which is the most promising truck application for fuel cell powertrains. On the other hand, 700 bar compressed H_2 gas would provide a higher driving range due to a 70% higher volumetric density at the system level (Basma & Rodríguez, 2022). Automotive 700 bar hydrogen storage applications typically use hydrogen tanks with a non-metallic inner liner made of composite materials encased in carbon fiber-reinforced structure, in what is known as Type VI tanks. Compared to 350 bar tanks, 700 bar Type IV tanks can have approximately 10% higher costs (CNHI, 2020).

An emerging storage option is liquid or cryogenic hydrogen storage, which requires temperatures as low as -253°C. Cryogenic hydrogen storage enables even longer drive ranges than 700 bar compressed storage because of the higher volumetric density, while at the same time reducing cost 35% relative to compressed hydrogen gas storage (CNHI, 2020). However, cryogenic hydrogen storage is still at a nascent stage, with a low technology readiness level, and faces logistical and technical challenges, such as H_2 tank boil-off losses and the need for hydrogen liquefaction (Basma & Rodríguez, 2022). For this reason, we only use cost data for gaseous hydrogen storage made of carbon fiber composite in this analysis.

Figure 6 shows the range of costs of hydrogen storage systems per kg of hydrogen from 2020 to 2040, with the dashed line representing ICCT's estimate. The latter is based on the data collected by Ricardo Strategic Consulting (2021) and Interact Analysis (2022) from primary research, as well as data from Transport & Environment (2021), Hunter et al. (2021), and Burke and Sinha (2020). Primary research is weighted three times as high as secondary research to develop the ICCT cost curve.

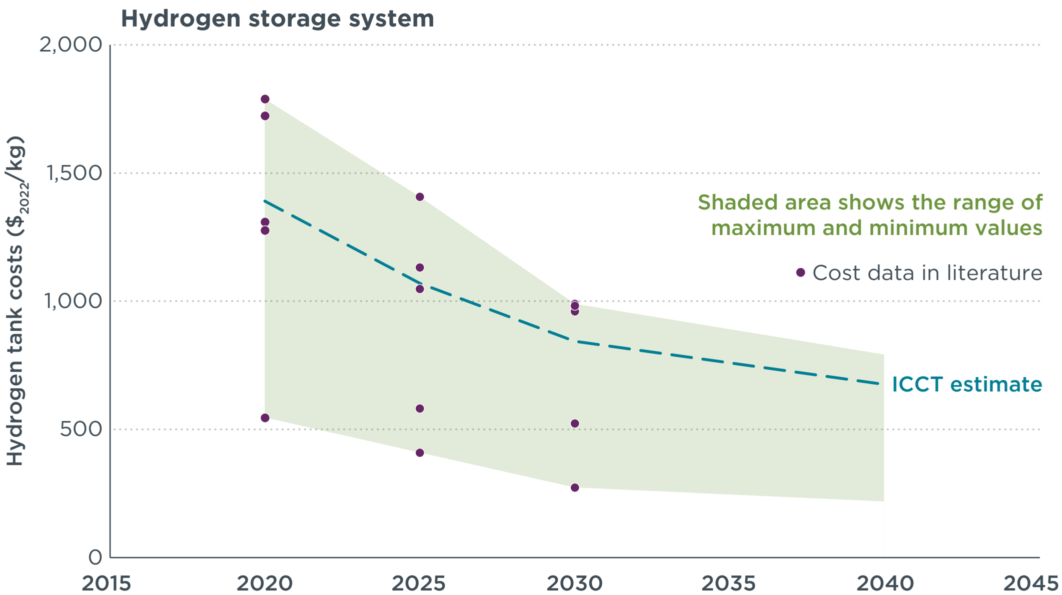

Figure 6. Estimates for the direct manufacturing cost of 700 bar compressed hydrogen storage systems

We estimated the cost of a hydrogen fuel Type IV tank to be $1,390 per kg of usable hydrogen in 2020, with reported costs ranging between $546/kg (Burke & Sinha, 2020) and $1,723/kg (Ricardo Strategic Consulting, 2021). As with other components, the costs of hydrogen tanks are expected to decline in the next two decades to an average of $675/kg in 2040. The reported costs of hydrogen storage systems are summarized in Table 5.

Table 5. Summary of collected data and ICCT estimates for the unit cost of hydrogen storage tanks

Hydrogen fuel tank cost ($/kg)				
	2027	2030	2033	2036
Minimum	355	273	257	240
Maximum	1240	989	930	871
ICCT estimate	979	844	794	743

Electric drive

The electric drive unit consists of three main modules: the inverter, the gearbox, and the electric motor. Electric trucks typically use induction motors or permanent-magnet motors, which are more efficient than their induction counterparts (Basma et al., 2021). The power electronics serve as the interface between the battery and the electric motor and transform direct current from the battery into alternating current to drive the motor. The gearbox converts the high-speed output from the electric motor into torque that can be applied at a wide range of vehicle speeds. Electric trucks commonly employ e-axle technology, which combines the motor, gearbox, and differential into a single and compact component. While e-axles are a nascent technology, it can unlock costs savings for housing and wiring and other non-recurring engineering costs (Interact Analysis, 2022).

Figure 7 shows the range of costs of the electric drive per unit of power (kW) from 2020 to 2040, with the dashed line representing ICCT's estimate. The latter is based on the data collected by Ricardo Strategic Consulting (2021) and Interact Analysis (2022) from primary research, as well as data from Burke and Sinha (2020). Primary research is weighted twice as high as secondary research to develop the ICCT cost curve.

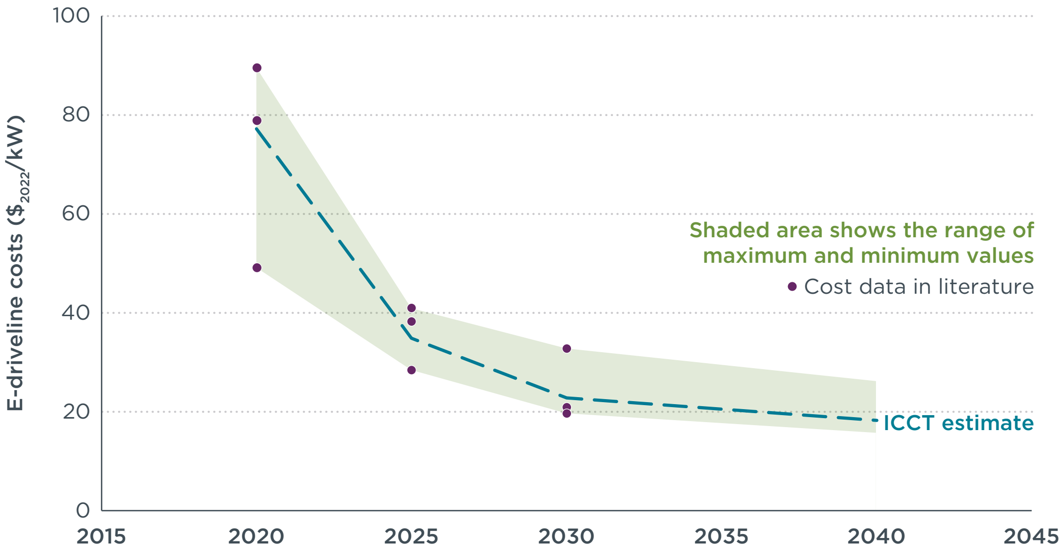

Figure 7. Estimates for the direct manufacturing cost of electric drive systems (motor, inverter, gearbox and peripheral components)

For 2020, we estimated the cost of electric drive units at around $77 per kW of electric motor continuous nominal power. This is expected to drop to $18/kW by 2040. The spread between the collected data is smaller than what was observed for other technologies. Of all data sources, the estimates from Ricardo Strategic Consulting showed the steepest learning curve, going from $90/kW in 2020—the highest estimate from the collected data—to about $20/kW in 2030—the lowest point from the data used. Burke and Sinha (2020) reported the lowest estimate for 2020 costs at $49/kW, while also predicting the highest costs in 2030 at $33/kW. These data are summarized in Table 6.

Table 6. Summary of collected data and ICCT estimates for the unit cost of electric drives

Electric drive unit cost ($/kW of continuous motor power)				
	2027	**2030**	**2033**	**2036**
Minimum	25	20	18	17
Maximum	38	33	31	29
ICCT estimate	30	23	21	20

Auxiliary components

In addition to the main zero-emission powertrain components already described, ZE-HDV require several auxiliary electrified components with various functions, such as braking, steering, air conditioning and heating, thermal management, and other high- and medium-voltage electric equipment. These components are responsible for 10% to 15% of zero-emission truck costs (Ricardo Strategic Consulting, 2021). Other than Ricardo Strategic Consulting data, no other source in the literature provides data on the costs of auxiliary components. Ricardo's estimates are, therefore, the only source of information used in this assessment. The respective low, medium, and high-cost estimates are summarized in Table 7. The cost of onboard chargers is estimated to decrease by 19% in 2025 and 28% in 2030, compared to 2020. The cost of the remaining auxiliary systems is forecasted to remain unchanged by Ricardo. The values presented in Table 7 are those presented in a previous ICCT report, adjusted to 2022 U.S. dollars (Sharpe & Basma, 2022).

Table 7. Summary of auxiliary electric component costs in 2020 as reported by Ricardo Strategic Consulting (in 2022 USD)

Component	2020 cost ($\$_{2022}$/kW)		
	Low	Medium	High
High voltage distribution, battery electric truck	21	30	41
High voltage distribution, fuel cell truck	21	27	35
Electric air brake compressor system	1,187	1,648	2,088
Electric steering pump	220	330	428
PTC heater	49	82	126
Air conditioning unit	52	77	137
Thermal management, battery electric truck	19	23	30
Thermal management, fuel cell truck	9	10	12
Onboard charger, battery electric truck	49	79	165
Onboard charger, hydrogen fuel cell truck	44	74	110

The power-specific auxiliary costs are used in the following ways to estimate their cost at the vehicle level:

» High voltage system costs are parameterized for each ZE-HDV as a function of the nominal power of the electric motor in continuous operation

» Heating, ventilation, and air conditioning systems are assumed to have 20 kW of power for sleeper cabins and 10 kW for day cabins.

» The electric air brake compressor system is assumed to require between 3 kW and 6 kW of power depending on the HDV segment

» The electric steering pump is assumed to require between 5 kW and 9 kW of power depending on the HDV segment

» The battery thermal management system cost is parameterized as function of the nominal power of the electric motor in continuous operation

» On-board chargers, converting AC power to DC current for battery charging, are assumed to have between 11 kW and 44 kW depending on the HDV segment

Cost of ZE-HDVs in the United States from 2022 to 2040

To estimate the list sale price of ZE-HDVs, we used the component costs presented in the previous section to do a bottom-up assessment for various HDV segments in the U.S. market, including Class 4 to Class 8 rigid trucks and tractor-trucks. The price estimates for each segment across three powertrains are presented in Table A1 to Table A5. The following section presents vehicle specifications modeled, as well as the detailed breakdown of the component costs for rigid and tractor trucks.

Class 4–5 rigid truck

Class 4–5 rigid trucks, which have a Gross Vehicle Weight Rating (GVWR) between 14,001 and 16,000 pounds, are commonly used for urban and regional delivery applications (Figure 8).

Figure 8. A Class-4 box truck

Between 2022 and 2040, efficiency improvements from 1.04 miles/kWh to 1.20 miles/kWh can reduce the battery pack size from 135 kWh to 112 kWh to achieve the same performance and range. Similarly, the size of hydrogen tanks for fuel cell trucks will decrease from 8 kg to 6 kg. The specifications for battery-electric and fuel-cell powertrains and auxiliary systems are summarized in Table 8.

Table 8. Vehicle specifications used to estimate the list price of Class 4–5 ZE-HDVs

Class 4–5	Battery electric truck	Fuel cell truck
Drive nominal power	250 kW	
Battery capacity	135 kWh (2022) 122 kWh (2030) 112 kWh (2040)	50 kWh
Fuel economy	1.04 miles/kWh (2022) 1.15 miles/kWh (2030), 1.20 miles/kWh (2040)	
Fuel cell power		180 kW
Hydrogen tank		8 kg (2022) 6 kg (2030) 6 kg (2040)
Air compressor power	3 kW	
Steering pump power	5 kW	
PTC heater power	10 kW	
Air conditioning unit	10 kW	
On-board charger	11 kW	

The greatest cost component for a battery electric Class 4–5 rigid truck in 2022 is indirect costs, accounting for more than 30% of the retail price. By 2030, indirect costs and battery costs will be halved, based on the ICM values from Table 2. As explained earlier, fuel cell is the most expensive component for hydrogen fuel-cell trucks. The cost of fuel cells will plummet to about 40% of their 2022 levels in 2030 and decrease by 26% in 2040.

The combined effect of improved technology and reduced costs is that battery electric Class 4–5 rigid trucks will reach price parity with diesel equivalent before 2030. As Figure 9 shows, compared to 2022 levels, the price of a battery electric Class 4–5 rigid truck will decrease from more than $123,000 to around $79,000 in 2030 and around $72,000 in 2040, which is 36% and 42% lower than in 2022, respectively. By then, battery electric will become the least expensive technology option, at 81% of the diesel truck price. The price for a fuel cell Class 4–5 rigid truck will also decrease significantly from more than $350,000 in 2022 to $156,000 in 2030 and reach $131,000 in 2040. Still, hydrogen fuel cells will remain the most expensive technology for this truck class and will not reach price parity with diesel trucks.

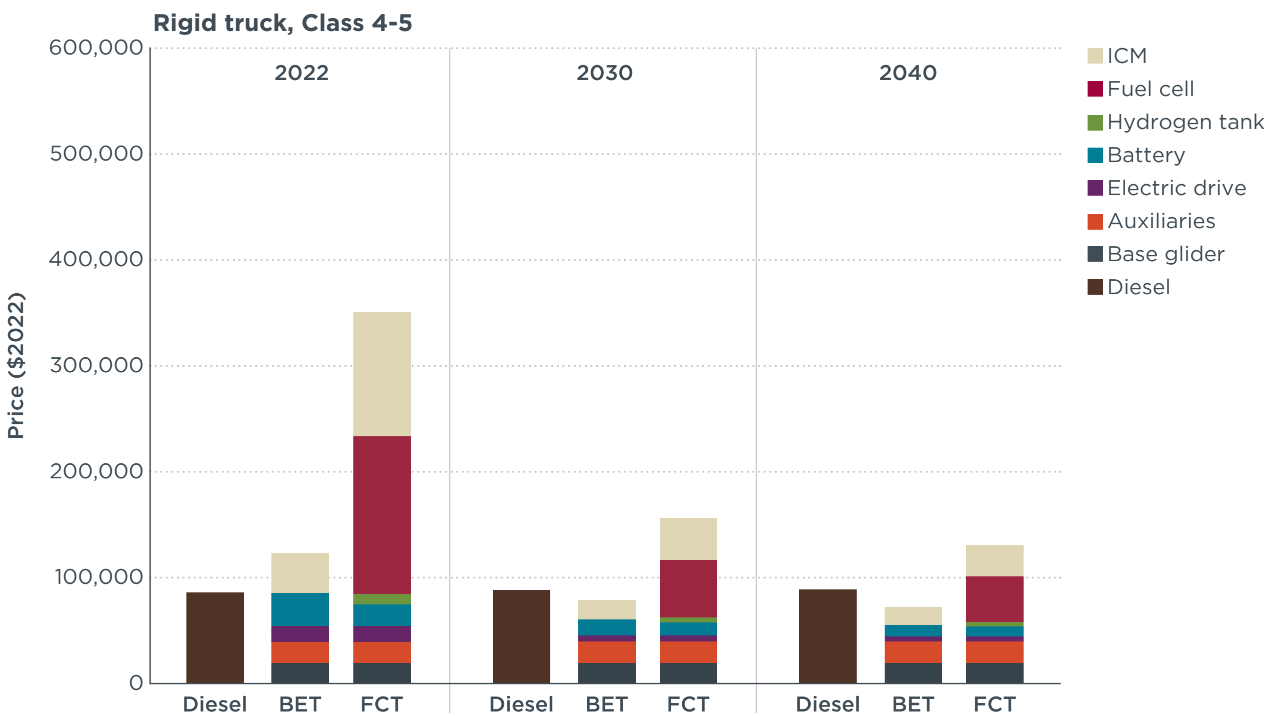

Figure 9. Estimated retail price of a Class 4–5 rigid truck in 2022, 2030, and 2040, broken down by separate component areas

Class 6–7 rigid truck

Class 6–7 rigid trucks have GVWR between 19,501 lbs. and 33,000 lbs. They are versatile in application, including transporting construction materials, food, and furniture (Figure 10).

Figure 10. A Class 7 straight truck

The sizing of the motor, battery packs, and hydrogen fuel tanks is slightly larger than Class 4–5 rigid trucks, which reflects their higher payloads and longer driving distances for Class 6–7 rigid trucks. These specifications are summarized in Table 9.

Table 9. Vehicle specifications used to estimate the list price of Class 6–7 ZE-HDVs

Class 6–7	Battery electric truck	Fuel cell truck
Drive nominal power	300 kW	
Battery capacity	205 kWh (2022) 185 kWh (2030) 170 kWh (2040)	70 kWh
Fuel economy	0.80 miles/kWh (2022) 0.89 miles/kWh (2030) 0.93 miles/kWh (2040)	
Fuel cell power		200 kW
Hydrogen tank i		12 kg (2022) 9 kg (2030) 9 kg (2040)
Air compressor power	3 kW	
Steering pump power	5 kW	
PTC heater power	10 kW	
Air conditioning unit	10 kW	
On-board charger	11 kW	

As seen in Figure 11, a battery electric truck in this class costs 43% more than a diesel baseline vehicle today, and a fuel-cell electric truck is around 2.6 times the price of a battery-electric one. Driven by decreases in battery costs and indirect costs, the price of a battery electric Class 6–7 rigid truck will drop by 39% in 2030, from close to $160,000 to about $98,000. In 2040, the price is estimated to be $89,000, 44% lower than in 2022. Battery electric technology will reach price parity with a diesel truck before 2030. Like Class 4–5 rigid trucks, fuel cell technology, with a cost of around $154,000, is unable to reach price parity with diesel, despite significant cost reductions of more than 62% compared to price levels in 2022.

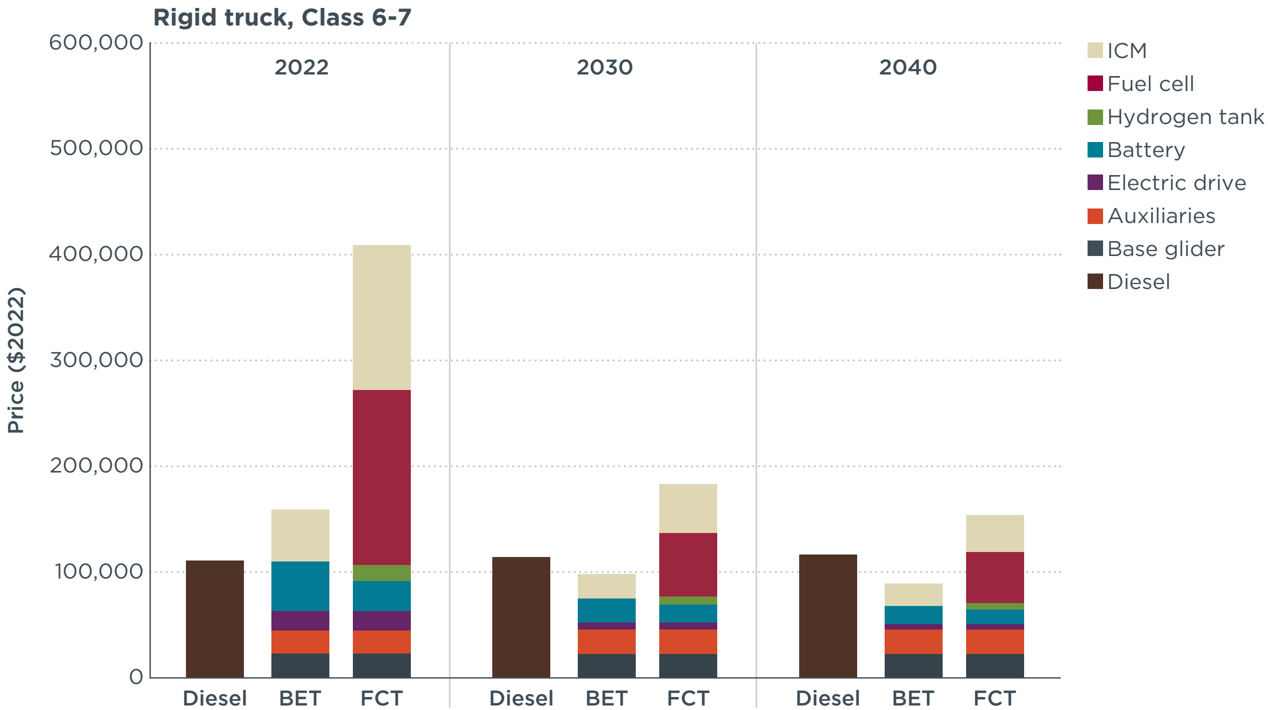

Figure 11. Estimated retail price of a rigid truck, Class 6-7, in 2022, 2030 and 2040, broken down by separate component areas

Class 8 rigid truck

Class 8 rigid trucks are the heaviest rigid trucks, with GVWRs above 33,000 lbs (Figure 12). Dump trucks and other vocational trucks typically belong to this category.

Figure 12. A Class 8 dump truck

Table 10 summarizes the specifications of Class 8 rigid trucks in our analysis. As a result of increased vehicle payload, the chief cost component for battery electric trucks in this truck class is the 400-kWh battery pack, which we estimate to cost 34% of the total vehicle price in 2022. Indirect costs account for 30% of the retail price. For hydrogen fuel cell trucks, the fuel cell contributes the most to the total price in 2022 (35%), followed by indirect costs (33%). We reflect efficiency improvements by adjusting the sizes of battery packs and hydrogen storage tanks in future years.

Table 10. Vehicle specifications used to estimate the list price of Class 8 rigid ZE-HDVs

Class 8	Battery electric truck	Fuel cell truck
Drive nominal power	350 kW	
Battery capacity	400 kWh (2022) 361 kWh (2030) 332 kWh (2040)	70 kWh
Fuel economy	0.51 miles/kWh (2022) 0.56 miles/kWh (2030) 0.58 miles/kWh (2040)	
Fuel cell power		200 kW
Hydrogen tank in		20 kg (2022) 14 kg (2030) 13 kg (2040)
Air compressor power	6 kW	
Steering pump power	9 kW	
PTC heater power	10 kW	
Air conditioning unit	10 kW	
On-board charger	22 kW	

Figure 13 presents the estimated retail prices for Class 8 diesel, battery electric, and fuel-cell electric rigid trucks in 2022, 2030, and 2040. Our analysis shows that the price of a battery electric Class 8 rigid truck will decrease from the 2022 level of $270,000 by 38% to $167,000 in 2030, and 45% to $150,000 in 2040. Price parity with diesel vehicles will be achieved before 2035. Even though the price of a fuel cell truck will experience a rapid decline from $472,000 today to $198,000 in 2040, the technology fails to reach price parity for this class of trucks.

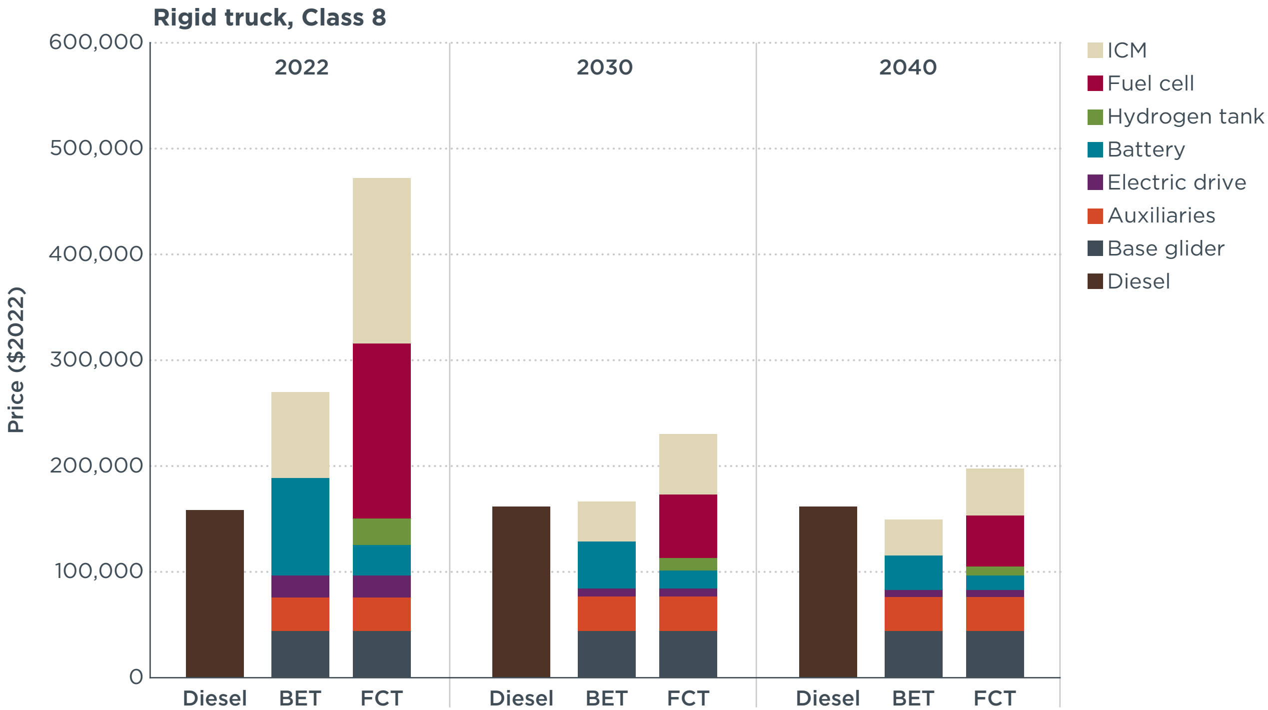

Figure 13. Estimated retail price of a rigid truck, Class 8, in 2022, 2030 and 2040, broken down by separate component areas

Short-haul tractor truck

Short-haul tractor trucks are used as beverage trucks and drayage trucks (Figure 14). They have predictable routes, return to fixed yards after daily operations, and generally do not travel more than 180 miles in a day. Truck manufacturers, including Daimler, Volvo, and Paccar have begun production of battery electric short-haul tractor models.

Figure 14. A short-haul tractor truck with a trailer attached

With a higher payload in this truck class, battery electric trucks need larger battery capacities, and hydrogen fuel-cell electric trucks require greater volumes of hydrogen storage. The power of on-board charger also doubles to 44 kW compared to a Class 8 rigid truck. The specifications for Class 8 short-haul tractor trucks in our analysis are summarized below.

Table 11. Vehicle specifications used to estimate the list price of Class 8 ZE short-haul tractor trucks

Short-haul tractor	Battery-electric truck	Fuel cell truck
Drive nominal power	350 kW	
Battery capacity	455 kWh (2022) 41 kWh (2030) 378 kWh (2040)	70 kWh
Fuel economy	0.43 miles/kWh (2022) 0.48 miles/kWh (2030) 0.50 miles/kWh (2040)	
Fuel cell power		210 kW
Hydrogen tank		26 kg (2022) 18 kg (2030) 16 kg (2040)
Air compressor power	6 kW	
Steering pump power	9 kW	
PTC heater power	10 kW	
Air conditioning unit	10 kW	
On-board charger	44 kW	

As Figure 15 presents, at $279,000 and $488,000 apiece, both battery-electric and fuel-cell electric Class 8 short-haul tractor trucks are much more expensive than a diesel truck ($150,000) in 2022. Consistent with other truck classes, battery pack costs (38%) and indirect costs (30%) contribute the most to the high price of battery electric trucks, while fuel cell costs (36%) and indirect costs (33%) account for the bulk of the price of hydrogen fuel cell trucks.

In 2030, the prices of a battery electric and a hydrogen fuel-cell electric Class 8 short-haul tractor truck will decrease by 41% and 53%, to $166,000 and $231,000, respectively. Neither will achieve price parity with diesel trucks by 2030, but battery electric trucks will be less expensive than diesel in this truck class in 2035. By 2040, battery electric and fuel-cell electric Class 8 short-haul tractor trucks will cost only 53% and 40% of their 2022 prices, respectively. Hydrogen fuel cell technology is again unable to reach price parity with diesel trucks in the timeframe of our analysis.

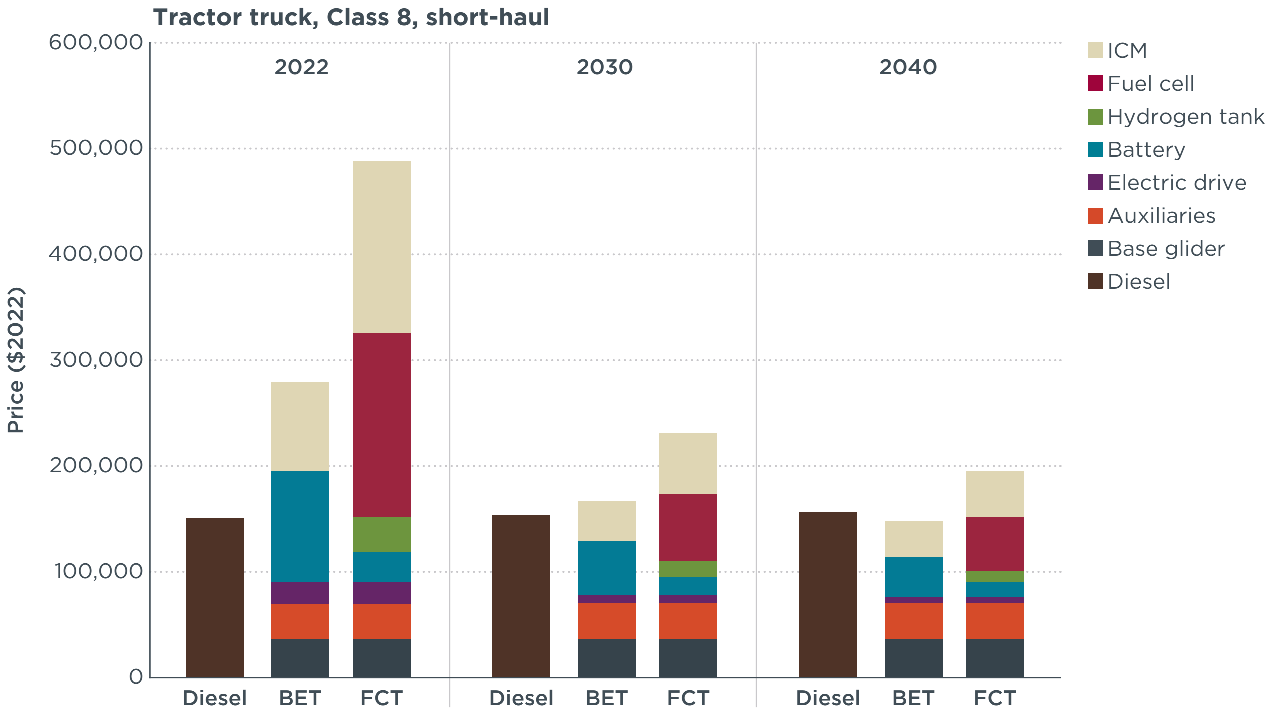

Figure 15. Estimated retail price of a short-haul tractor truck, Class 8, in 2022, 2030 and 2040, broken down by separate component areas

Long-haul tractor truck

Compared to short-haul tractor trucks, the daily mileage of long-haul tractor trucks is higher, and many trucks are fitted with sleeper cabs to enable round-the-clock operations (Figure 16).

Figure 16. A sleeper-cab tractor truck with a trailer attached

Long-haul tractor trucks have demanding duty cycles that require large energy storage systems. We estimate that in 2022, the battery capacity required to sustain normal operations will be 1,150 kWh for a battery electric truck, and fuel-cell electric models will require a 53 kg hydrogen tank. Under these conditions, battery costs alone will contribute to more than half the total vehicle price for battery electric trucks in 2022. On the other hand, the most expensive component for hydrogen fuel cell trucks, i.e., fuel cells, do not scale linearly with vehicle size and payload, and hydrogen tanks are not as expensive. Indirect costs contribute the greatest to the total price of hydrogen fuel-cell long-haul tractor trucks in 2022. In the next two decades, the sizes of energy storage systems for both battery-electric and hydrogen fuel-cell trucks will decrease as trucks achieve higher efficiency, bringing down the costs. Table 11 shows the changes in battery and hydrogen tank capacity and other vehicle specifications for Class 8 long-haul tractor trucks in our analysis.

Table 11. Vehicle specifications used to estimate the list price of Class 8 ZE long-haul tractor trucks

Short-haul tractor	Battery-electric truck	Fuel cell truck
Drive nominal power	350 kW	
Battery capacity	1150 kWh (2022) 990 kWh (2030) 865 kWh (2040)	70 kWh
Fuel economy	0.42 miles/kWh (2022) 0.49 miles/kWh (2030) 0.53 miles/kWh (2040)	
Fuel cell power		210 kW
Hydrogen tank		53 kg (2022) 35 kg (2030) 32 kg (2040)
Air compressor power	6 kW	
Steering pump power	9 kW	
PTC heater power	10 kW	
Air conditioning unit	10 kW	
On-board charger	44 kW	

Like the trend for other truck classes in our analysis, the next two decades will see drastic decreases in the price of battery-electric and hydrogen fuel-cell electric Class 8 long-haul tractor trucks (Figure 17). From the current costs of $515,000 and $548,000, the prices of a battery electric and a hydrogen fuel-cell electric Class 8 long-haul tractor truck will decrease by 49% and 53%, respectively, in 2030. The price reductions compared to 2022 will be 58% and 60% for battery electric and fuel-cell electric Class 8 short-haul tractor trucks, respectively, in 2040. Fuel cell technology will cost less than battery electric for this truck class starting from 2029. However, neither technology will achieve price parity with diesel trucks. Zero-emission Class 8 long-haul tractor trucks are the only class of trucks in this analysis that will remain more expensive than diesel equivalents in 2040.

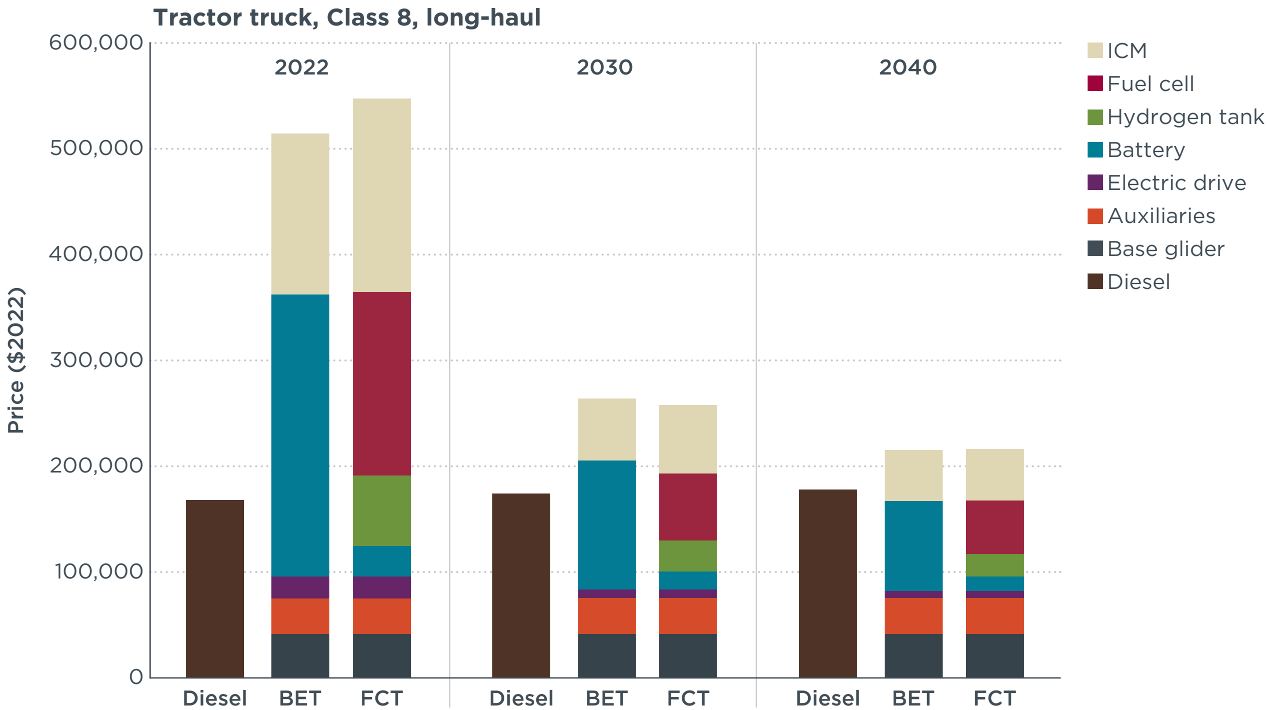

Figure 17. Estimated retail price of a long-haul tractor truck, Class 8, in 2022, 2030 and 2040, broken down by separate component areas

Summary

This study reviews recent literature on current and projected battery-electric and hydrogen fuel cell tractor truck costs and updates a previous ICCT publication on the subject. The assessment includes the latest data from new primary research with suppliers and industry conducted by Interact Analysis, extends the cost assessment to 2040, provides estimates for the list prices of all relevant HDV segments in the United States, and provides the results in 2022 U.S. dollars.

We find that:

» While battery costs for ZE-HDVs lag behind electric cars in cost reduction, their costs are expected to halve by 2030 compared to 2022, reaching $120/kWh at the pack level. The reductions of battery costs are one of the largest contributors to enabling price parity between battery-electric and diesel trucks.

» Fuel cell systems are also expected to see costs drop by nearly two-thirds dramatically by 2030 compared to current levels, reaching $300/kW. Hydrogen tank costs are expected to drop by only one-third over the same period, reaching $850/kg of hydrogen.

» Electric drive systems—including the transmission, motor, and inverter—are forecasted to see cost reductions of over 60% by 2030, reaching $23/kW.

» The upfront cost parity between battery electric trucks and their diesel counterparts is expected to be achieved in the late 2020s or early 2030s for most truck segments. The exception is long-haul tractor-trucks, for which the large batteries will continue to be the dominant cost item. By 2040, fuel-cell electric trucks will have a similar price to battery-electric and diesel trucks.

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Appendix: Detailed price evolution and cost breakdown

Table A1. Forecast of Class 4-5 straight truck price evolution from 2022 to 2040 for diesel, battery electric, and fuel cell powertrains in 2022 US dollars

Year	Diesel	Battery electric	Hydrogen fuel-cell electric
2022	86k	123k	351k
2023	86k	117k	324k
2024	87k	111k	298k
2025	87k	105k	273k
2026	88k	99k	249k
2027	88k	94k	225k
2028	88k	89k	201k
2029	88k	84k	178k
2030	88k	79k	156k
2031	88k	78k	153k
2032	88k	77k	151k
2033	89k	77k	148k
2034	89k	76k	146k
2035	89k	75k	143k
2036	89k	75k	141k
2037	89k	74k	138k
2038	89k	73k	136k
2039	89k	73k	133k
2040	89k	72k	131k

Table A2. Forecast of Class 6-7 straight truck price evolution from 2022 to 2040 for diesel, battery electric, and fuel cell powertrains in 2022 US dollars

Year	Diesel	Battery electric	Hydrogen fuel-cell electric
2022	111k	159k	409k
2023	112k	151k	378k
2024	112k	142k	348k
2025	112k	135k	319k
2026	113k	127k	291k
2027	113k	119k	263k
2028	113k	112k	236k
2029	114k	105k	209k
2030	114k	98k	184k
2031	115k	97k	181k
2032	115k	96k	178k
2033	116k	95k	174k
2034	116k	94k	171k
2035	117k	94k	168k
2036	117k	93k	165k
2037	117k	92k	163k
2038	117k	91k	160k
2039	117k	90k	157k
2040	117k	89k	154k

Table A3. Forecast of Class 8 straight truck price evolution from 2022 to 2040 for diesel, battery electric, and fuel cell powertrains in 2022 US dollars

Year	Diesel	Battery electric	Hydrogen fuel-cell electric
2022	158k	270k	472k
2023	159k	256k	439k
2024	160k	241k	407k
2025	161k	228k	375k
2026	161k	215k	345k
2027	162k	202k	315k
2028	162k	190k	286k
2029	162k	178k	258k
2030	162k	167k	230k
2031	162k	165k	227k
2032	162k	163k	223k
2033	162k	161k	220k
2034	162k	160k	217k
2035	162k	158k	214k
2036	162k	156k	210k
2037	162k	155k	207k
2038	162k	153k	204k
2039	162k	151k	201k
2040	162k	150k	198k

Table A4. Forecast of Class 8 short-haul tractor truck price evolution from 2022 to 2040 for diesel, battery electric, and fuel cell powertrains in 2022 US dollars

Year	Diesel	Battery electric	Hydrogen fuel-cell electric
2022	150k	279k	488k
2023	151k	263k	452k
2024	151k	248k	418k
2025	151k	233k	385k
2026	151k	219k	352k
2027	151k	205k	321k
2028	152k	192k	290k
2029	152k	179k	260k
2030	153k	166k	231k
2031	154k	164k	227k
2032	155k	163k	224k
2033	155k	161k	220k
2034	156k	159k	216k
2035	157k	157k	213k
2036	157k	155k	209k
2037	157k	153k	206k
2038	157k	151k	202k
2039	157k	149k	199k
2040	157k	148k	196k

Table A5. Forecast of Class 8 long-haul tractor truck price evolution from 2022 to 2040 for diesel, battery electric, and fuel cell powertrains in 2022 US dollars

Year	Diesel	Battery electric	Hydrogen fuel-cell electric
2022	168k	515k	548k
2023	169k	478k	507k
2024	170k	443k	468k
2025	171k	410k	430k
2026	172k	378k	393k
2027	172k	348k	358k
2028	173k	318k	323k
2029	174k	291k	290k
2030	175k	264k	258k
2031	175k	259k	254k
2032	176k	254k	249k
2033	177k	249k	245k
2034	178k	244k	241k
2035	178k	239k	237k
2036	178k	234k	232k
2037	178k	230k	228k
2038	178k	225k	224k
2039	178k	220k	220k
2040	178k	216k	217k

Table A6. Component cost breakdown for battery-electric trucks in 2022, 2030, and 2040

BET	2022	2030	2040
	Rigid truck, Class 4–5		
Base glider	19k	19k	19k
Auxiliaries	21k	21k	21k
E-drive	15k	6k	5k
Battery	31k	15k	11k
Indirect costs	38k	18k	17k
	Rigid truck, Class 6–7		
Base glider	23k	23k	23k
Auxiliaries	23k	23k	23k
E-drive	18k	7k	5k
Battery	47k	23k	17k
Indirect costs	49k	23k	21k
	Rigid truck, Class 8		
Base glider	44k	44k	44k
Auxiliaries	32k	32k	32k
E-drive	21k	8k	6k
Battery	92k	44k	33k
Indirect costs	81k	38k	34k

BET	2022	2030	2040
	Tractor truck, short-haul		
Base glider	36k	36k	36k
Auxiliaries	34k	34k	34k
E-drive	21k	8k	6k
Battery	105k	51k	37k
Indirect costs	84k	38k	34k
	Tractor truck, long-haul		
Base glider	42k	42k	42k
Auxiliaries	34k	34k	34k
E-drive	21k	8k	6k
Battery	266k	122k	85k
Indirect costs	152k	58k	48k

Table A7. Component cost breakdown for fuel cell trucks in 2022, 2030, and 2040

FCT	2022	2030	2040
	Rigid truck, Class 4–5		
Base glider	19k	19k	19k
Auxiliaries	21k	21k	21k
E-drive	15k	6k	5k
Battery	20k	12k	10k
H2 Tank	10k	5k	4k
Fuel cell	149k	54k	43k
Indirect costs	118k	39k	29k
	Rigid truck, Class 6–7		
Base glider	23k	23k	23k
Auxiliaries	23k	23k	23k
E-drive	18k	7k	5k
Battery	29k	17k	14k
H2 Tank	15k	8k	6k
Fuel cell	165k	60k	48k
Indirect costs	137k	46k	35k
	Rigid truck, Class 8		
Base glider	44k	44k	44k
Auxiliaries	32k	32k	32k
E-drive	21k	8k	6k
Battery	29k	17k	14k
H2 Tank	25k	12k	9k
Fuel cell	165k	60k	48k
Indirect costs	156k	57k	44k

FCT	2022	2030	2040
	Tractor truck, short-haul		
Base glider	36k	36k	36k
Auxiliaries	34k	34k	34k
E-drive	21k	8k	6k
Battery	29k	17k	14k
H2 Tank	33k	15k	11k
Fuel cell	173k	63k	51k
Indirect costs	162k	57k	44k
	Tractor truck, long-haul		
Base glider	42k	42k	42k
Auxiliaries	34k	34k	34k
E-drive	21k	8k	6k
Battery	29k	17k	14k
H2 Tank	67k	29k	22k
Fuel cell	173k	63k	51k
Indirect costs	183k	64k	48k