WHITE PAPER

APRIL 2023

# TOTAL COST OF OWNERSHIP OF ALTERNATIVE POWERTRAIN TECHNOLOGIES FOR CLASS 8 LONG-HAUL TRUCKS IN THE UNITED STATES

Hussein Basma, Claire Buysse, Yuanrong Zhou, and Felipe Rodríguez

www.theicct.org

communications@theicct.org

twitter @theicct

THE INTERNATIONAL COUNCIL
ON CLEAN TRANSPORTATION

BEIJING | BERLIN | SAN FRANCISCO | SÃO PAULO | WASHINGTON

## ACKNOWLEDGMENTS

The authors thank all internal reviewers of this report for their guidance and constructive comments, with special thanks to Oscar Delgado, Stephanie Searle, Ben Sharpe, Charlie Allcock, Ray Minjares, and Logan Pearce (International Council on Clean Transportation). Their reviews do not imply any endorsement of the content of this report, and any errors are the authors' own.

Editor: Amy Smorodin

For additional information:

International Council on Clean Transportation
1500 K Street NW, Suite 650
Washington, DC 20005

communications@theicct.org | www.theicct.org | @TheICCT

This work was generously supported by the Climate Works Foundation. Responsibility for the information and views set out in this report lies with the authors. The Climate Works Foundation will not be held responsible for any use which may be made of the information contained or expressed herein.

# EXECUTIVE SUMMARY

Heavy-duty vehicles (HDVs) in the United States were responsible for more than a quarter of the transport sector's greenhouse gas (GHG) emissions in 2020. To regulate the sector's GHG emissions, the U.S. Environmental Protection Agency has implemented emission standards. The most recent update, Phase 2, extends from model years 2021 to 2027. The stringency of the standards was based on the improvement potential of HDVs powered by combustion engines. Zero-emission (ZE) HDVs, which have no tailpipe GHG or pollutant emissions, were not considered in the technology pathways underpinning the standards due to their lack of maturity when the standards were adopted in 2016.

Understanding that ZE HDVs are essential for decarbonizing the sector, some truck manufacturers in North America have announced plans to produce ZE trucks and buses at scale. The upcoming Phase 3 GHG standards for HDVs, proposed in early 2023, present an opportunity to review the stringency of the standards and consider the role ZE HDVs will play in deeply decarbonizing the HDV sector in the United States.

Despite their environmental benefits, the widespread adoption of ZE HDVs will only occur if it also leads to economic benefits. To shed light on their financial viability, this paper evaluates the total cost of ownership (TCO) of four different truck technologies: diesel, battery electric, hydrogen fuel-cell, and hydrogen combustion powertrains. We focus on Class 8 tractor-trailers operating in long-haul assuming a first ownership period of five years.

The study assesses the techno-economic performance at the U.S. state and national levels in the 2022–2040 timeframe. For the state analysis, seven representative states—California, Georgia, Illinois, New York, Florida, Texas, and Washington—were chosen due to their geographic coverage over the U.S. mainland, long-haul trucking activity in every geographic region, and differences in energy costs. At the national level, the analysis captures uncertainties in technology cost and representative variations in energy prices that a vehicle might face in cross-state operation.

We arrive at the following main findings:

**By 2030, the total cost of ownership of battery electric long-haul trucks will likely be lower than that of their diesel counterparts in all representative states considered in this analysis.** Despite their higher upfront price, battery electric trucks have substantially lower operational expenses than the other trucks studied, as shown in Figure ES1. This is driven by the higher energy efficiency of battery electric powertrains and their lower maintenance costs.

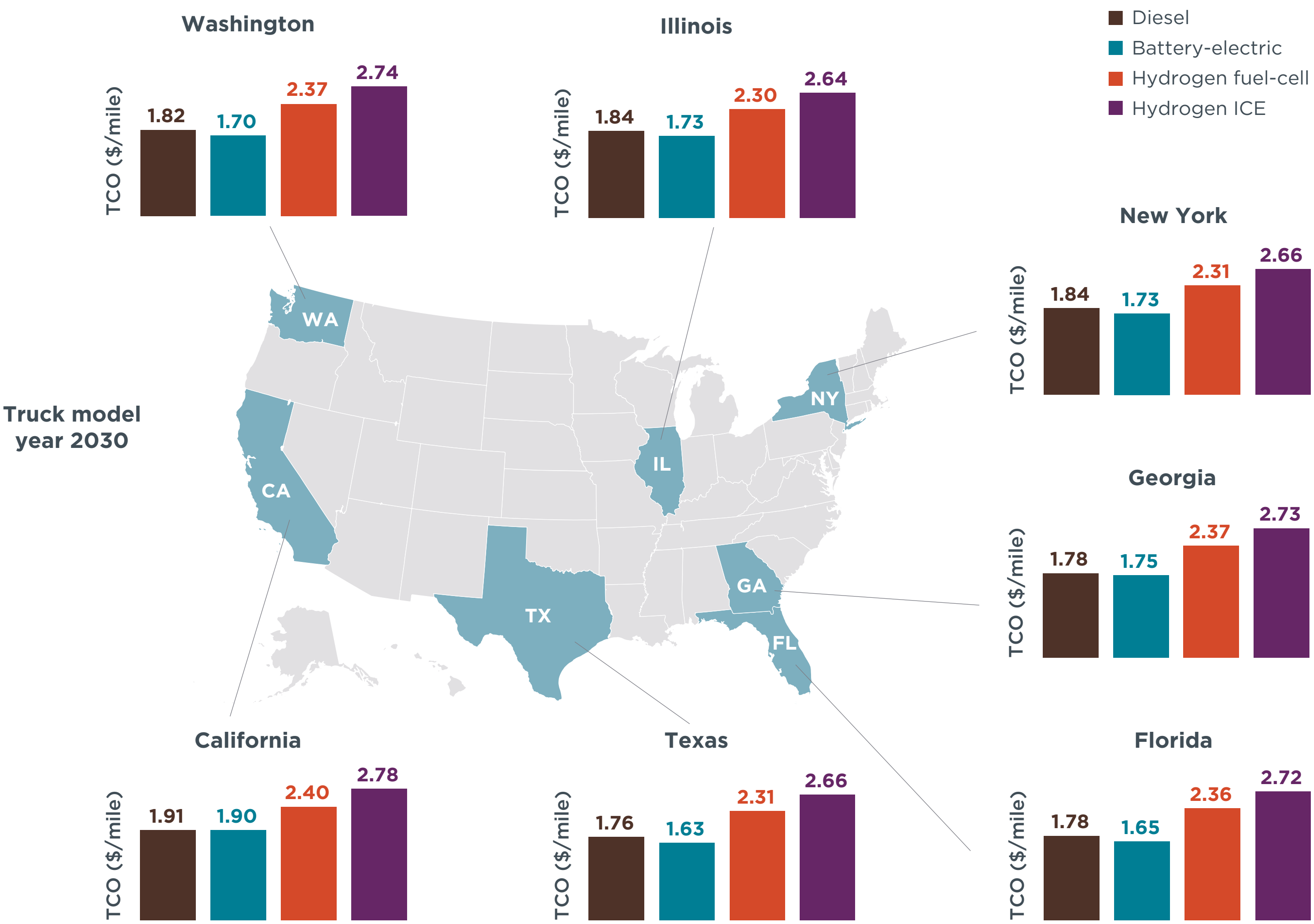


**Figure ES1.** State-specific total cost of ownership for different model year 2030 truck technologies.

**For very high daily mileages, battery electric trucks can still achieve a better total cost of ownership than their diesel counterparts.** As a truck's average daily mileage or mileage variability—defined as the percentage difference between the maximum and the average daily mileage—increases, larger batteries are needed to ensure the truck's daily energy needs are covered during average use and on the most demanding days. The larger batteries required increase the upfront price of battery electric trucks. Conversely, higher average daily mileage improves the operational costs of battery electric trucks compared to their diesel counterparts. Overall, battery electric trucks are expected to record a better TCO for average mileages as high as 750 miles per day, provided that the day-to-day milage variability is low (Figure ES2).

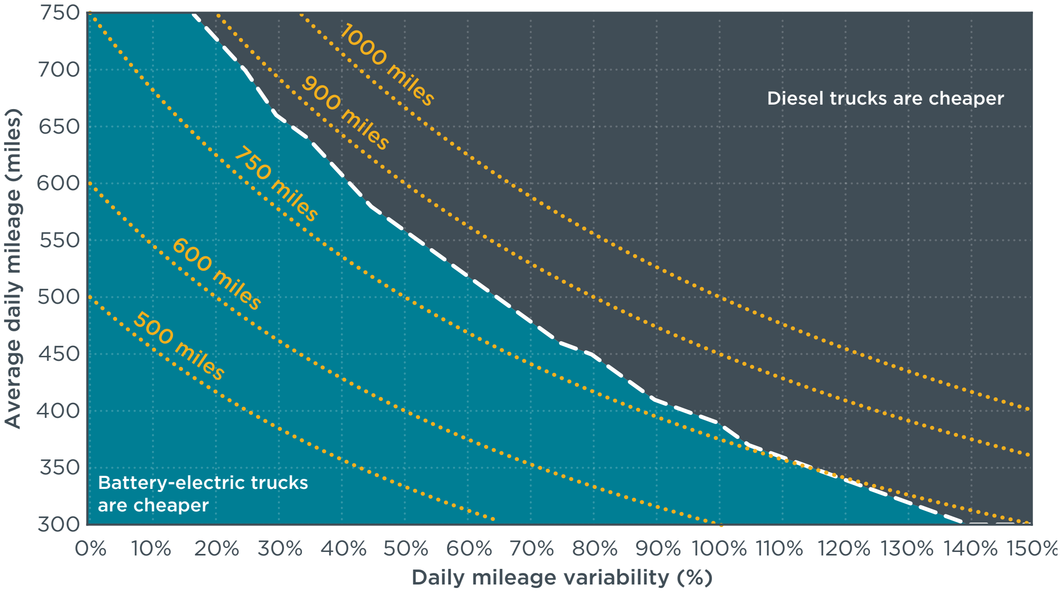


**Figure ES2.** Impact of daily mileage and mileage variability on the TCO of model year 2040 battery electric and diesel trucks. Daily mileage variability defined as the ratio of maximum to average daily mileage.

**Battery electric trucks have a lower total cost of ownership than hydrogen-powered trucks for long-haul applications, even when accounting for tax credits in the Inflation Reduction Act**. Lower fuel costs make battery electric trucks the most cost-effective zero-emission technology. With estimated charging costs ranging between \$0.15/kWh and \$0.30/kWh, green hydrogen fuel prices would need to be in the range of \$3.00/kg to \$6.50/kg for hydrogen fuel-cell trucks to reach TCO parity with battery electric trucks during the next decade. Hydrogen internal combustion engine trucks will require green hydrogen fuel prices as low was \$2.00/kg to reach TCO parity with battery electric trucks by 2030; This is much lower than the estimated green hydrogen price in 2030 (\$9.00/kg to \$11.00/kg) and 2040 (\$8.00/kg to \$10.00/kg) with the tax subsidies included in the Inflation Reduction Act, as shown in Figure ES3.

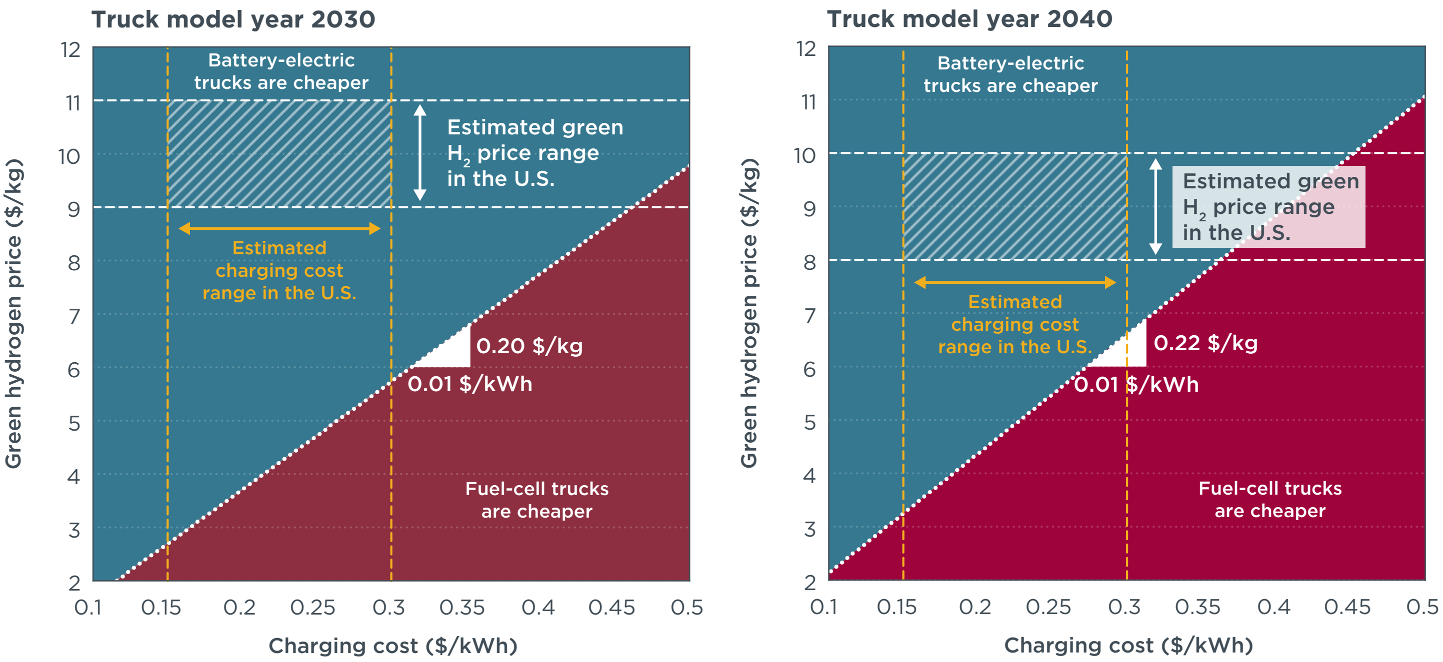


**Figure ES3.** Total cost of ownership parity sensitivity to charging costs and hydrogen fuel prices for several truck model years. The dashed area in the figure reflects the estimated charging costs and green hydrogen prices, including infrastructure deployment cost. The small triangles in the figure represent the line slope

The analysis presented in this study shows that zero-emission trucks can ensure a cost-effective transition away from fossil diesel, providing a substantial reduction in GHG emissions. Battery electric trucks operating in long-haul are likely to achieve a lower TCO than diesel trucks before the end of this decade in all states considered in this analysis.

# TABLE OF CONTENTS

# LIST OF ACRONYMS

| | |
|---|---|
| DMC | Direct manufacturing cost |
| GHG | Greenhouse gas |
| HDV | Heavy-duty vehicle |
| ICE | Internal combustion engine |
| ICM | Indirect cost multipliers |
| MPGe | Miles per gallon diesel equivalent |
| MSRP | Manufacturer suggested retail price |
| TCO | Total cost of ownership |
| VMT | Vehicle miles traveled |
| ZE | Zero emission |

# LIST OF FIGURES

## LIST OF TABLES

# INTRODUCTION

Heavy-duty vehicles (HDVs) are among the most significant sources of greenhouse gas (GHG) emissions in the United States. In 2020, HDVs were responsible for more than 27% of the total U.S. transport sector GHG emissions (U.S. Environmental Protection Agency, 2022a). While GHG emissions for most transport means recorded a decline over the past 30 years, the average HDV GHG emissions per vehicle increased by 83% in 2020 relative to 1990 levels and by 5% relative to 2005 levels, mainly driven by the increase in freight activity and a negligible improvement in vehicle fuel economy (U.S. Environmental Protection Agency, 2022a).

Greenhouse gas emissions from heavy-duty vehicles have historically been regulated at the federal level by increasingly stringent standards set by the U.S. Environmental Protection Agency. Last updated in 2016, the current Phase 2 GHG standards for HDVs were predicated on projected improvements in the efficiency of conventional internal combustion engine vehicles. While zero-emission (ZE) HDVs were not considered in setting the stringency of the rule, they were incentivized with super credits intended to support the nascent market. Zero-emission HDVs are defined as vehicles that have no tailpipe GHG or pollutant emissions. In the context of this study, this includes battery electric and hydrogen fuel-cell electric vehicles.

Zero-emission vehicles have a significant role in deeply decarbonizing the HDV sector in the United States, given the limited remaining GHG emission reduction potential for internal combustion engine (ICE) vehicles (Buysse, Sharp, & Delgado, 2021). Since the Phase 2 rulemaking, several states led by California have moved to require the deployment of ZE HDVs. The most notable is California's Advanced Clean Trucks rule, which requires manufacturers to sell an increasing percentage of ZE HDVs, starting at 5% in model year (MY) 2024 and increasing to 40% by 2035 (Buysse & Sharpe, 2020). In addition, several truck manufacturers in North America have announced plans to increase their production of new ZE truck models (Buysse, 2022; International Council on Clean Transportation, 2022). This includes 100% zero-emission sales commitments from major manufacturers like Daimler Trucks (Daimler Truck AG, 2023), Volvo Trucks (Volvo Trucks, 2022), and Navistar (McDaniel, 2022) by or before 2040. Nonetheless, the capital investment needed to transition to these technologies may hinder their wide deployment.

In this report, we evaluate the economic viability of several HDV truck technologies by estimating their total cost of ownership (TCO) over the most important use case in the United States: Class 8 tractor-trailers operating in the long-haul. This class is the most challenging HDV segment to decarbonize, given the trucks' high daily mileage and payloads. We compare four powertrain technologies: diesel, battery electric, hydrogen fuel-cell, and hydrogen internal combustion engine (ICE). The study looks at the TCO from the perspective of the first ownership period, assuming a holding period of five years. The TCO is quantified using detailed assumptions regarding current and future technology potential and costs.

# METHODS AND DATA SOURCES

## USE CASE DEFINITION

This paper studies the total cost of ownership of diesel, battery electric, hydrogen fuel-cell, and hydrogen internal combustion engine heavy trucks focusing on Class 8 long-haul high-roof sleeper cab trucks operating in the United States. The use case of interest considers a 500-mile average daily mileage. The annual vehicle miles traveled (VMT) curve is shown in Figure 1 as a function of the truck age based on information from MOVES3 (U.S. Environmental Protection Agency, 2022b).

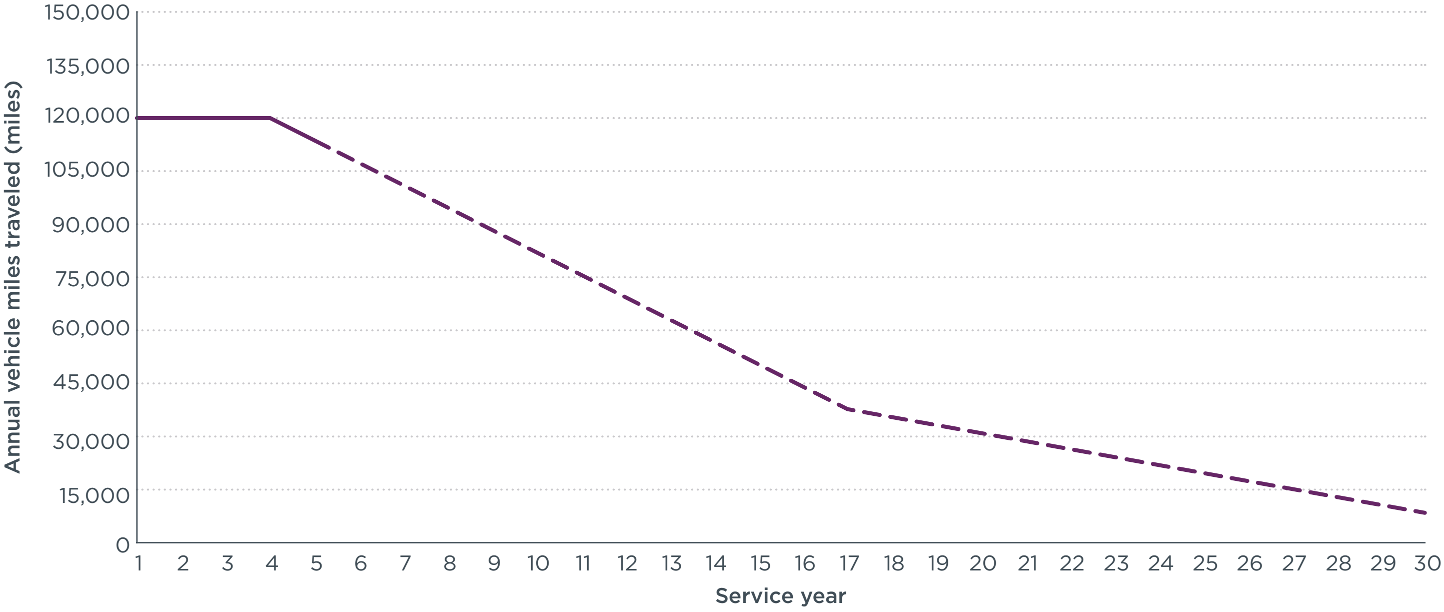


**Figure 1.** Long-haul truck annual mileage as a function of service years.

This TCO analysis is conducted at the state and national levels, considering state-specific and national-average energy and fuel cost data, respectively. For the state-specific analysis, the study focuses on California, Texas, Washington, Florida, Illinois, Georgia, and New York. These states are chosen based on the following criteria:

1. Ensuring comprehensive geographic coverage over the U.S. mainland.
2. Focusing on states with the highest long-haul trucking activity in every geographic region based on data available from Federal Highway Administration (2018).
3. Ensuring a comprehensive coverage of commercial electricity rates in the United States based on data from U.S. Energy Information Administration (2022a) to reflect charging costs variation among states.

At the national level, we conduct a stochastic Monte Carlo approach considering data from all 50 states, mainly on diesel fuel, hydrogen fuel, and electricity costs, in addition to data reflecting the uncertainties in technology costs, where the main TCO inputs are modeled as probability density functions with predefined ranges of uncertainties.

## FUEL CONSUMPTION MODELING AND ENERGY STORAGE SIZING

The fuel consumption of each truck technology is estimated through a multi-physical modeling approach using a commercial simulation tool (Simcenter Amesim, 2022). The models simulate the vehicle's longitudinal dynamics and the physical behavior of the main powertrain components, considering the vehicle road load parameters and technical specifications. More details about the development of the diesel, battery electric, and hydrogen fuel-cell powertrain models can be found in Basma, Beys, and Rodríguez (2021) and Basma and Rodríguez (2022). Regarding the hydrogen ICE powertrain modeling, the main difference relative to the diesel powertrain lies in the engine modeling. We model the hydrogen ICE as a spark-ignited engine in lean combustion mode. The hydrogen fuel specific heating value is 120 MJ/kg, and the air-fuel stoichiometric ratio is 34. Table 1 summarizes the common road load parameters and powertrain specifications among all technologies, and Table 2 summarizes the technology-specific powertrain components. The current technology parameters correspond to an average truck in 2022, while future technology parameters reflect the technology potential that can be achieved in 2035.

**Table 1.** Common road load parameters and powertrain specification for current (2022) and future (2035) technologies.

| Parameter | Current value (2022) | Future value (2035) |
|---|---|---|
| **Aerodynamic drag area** | 5.68 $m^2$ [a] | 4.4 $m^2$ [b] |
| **Rolling resistance coefficient** | 6.15 kg/t [a] | 4.1 kg/t [b] |
| **Wheel radius** | 0.49 m | 0.49 m |
| **Wheel inertia** | 22.5 $kgm^2$ | 22.5 $kgm^2$ |
| **Gear efficiency** [c] | 98.5% | 99.1% |
| **Final drive efficiency** [c] | 97% | 98% |
| **Trailer weight** | 13,500 lbs [a] | 10,850 lbs [b] |

a) U.S. EPA & U.S. DOT (2016)
b) Buysse et al. (2021)
c) Basma, Beys, et al. (2021)

**Table 2.** Technology-specific powertrain parameters for current (2022) and future (2035) powertrain technologies.

| | Diesel | | Battery electric | | Fuel cell | | $H_2$ ICE | |
|---|---|---|---|---|---|---|---|---|
| **Parameter** | Current | Future | Current | Future | Current | Future | Current | Future |
| **Power unit** [a] | 339 kW (445 HP) | | | | | | | |
| **Battery size** | - | | 1 MWh | 740 kWh | 70 kWh | | - | |
| **Fuel cell power** | - | | - | | 210 kW | | - | |
| **$H_2$ tank size** | - | | - | | 62 kg | 40 kg | 76 kg | 52 kg |
| **Peak break thermal efficiency** | 46% | 55% [b] | - | | - | | 44% | 50% [c] |
| **Peak fuel cell efficiency** | - | | - | | 60% | 67% | - | |
| **Gearbox (gear ratios)** | 10-speed (12.8, 9.25, 6.76, 4.9, 3.8, 2.61, 1.89, 1.38, 1, 0.73) | | 2-speed [5,1] | | 2-speed [5,1] | | 10-speed (12.8, 9.25, 6.76, 4.9, 3.8, 2.61, 1.89, 1.38, 1, 0.73) | |
| **Final drive ratio** | 3.31 | | 2 | | 2 | | 3.31 | |

a) Electric motor or engine rated power.
b) Buysse et al. (2021)
c) Loszka et al. (2022)

The battery in a battery electric truck is sized to meet a specific daily mileage. For this use case, the required daily mileage is 500 miles. We assume that the truck drivers stop for a 30-minute break every 190 miles (Phadke et al., 2021), which can be used to recharge the battery at a rate of 350 kW today and 1 MW as of 2027. The battery size is then estimated given the truck's electric energy consumption, charging power during the day, and required daily mileage. We also assume that the battery size will be, at most, 1 MWh due to payload and volume capacity constraints. When a larger battery is required, we assume that the drivers stop more frequently for charging, which will increase labor costs, as will be discussed later in the total cost of ownership modeling section. We also assume that the battery will be sized to provide at least 300 miles on a single charge. Table A1 in the appendix summarizes the battery sizing approach.

All powertrain models are simulated under the National Renewable Energy Laboratory long-haul cycle (National Renewable Energy Laboratory, 2023), and at a reference payload of 38,000 lb as defined in the U.S. Environmental Protection Agency's regulatory impact analysis of 2016 (U.S. Environmental Protection Agency & U.S. Department of Transportation, 2016). For battery electric trucks, the choice of battery size will significantly impact the fuel economy and maximum payload capacity, given the battery weight. On the other hand, the battery size depends on the truck's fuel economy, total vehicle weight, and driving mileage design point. In this case, an iterative approach is considered to size the battery and determine the truck's energy efficiency and maximum payload capacity.

Figure 2 summarizes the fuel economy of the simulated trucks for current and future vehicle technologies, expressed in miles per gallon diesel equivalent (MPGe). Battery electric is the most energy-efficient technology recording the highest fuel economy of around 13 MPGe for current vehicle technologies. This is almost twice as much as the diesel truck's fuel economy. Hydrogen fuel-cell trucks record an approximate 10% improvement in fuel economy relative to their diesel counterparts for current vehicle technologies. Hydrogen ICE trucks register the lowest fuel economy at 6 MPGe, almost 10% lower than their diesel counterparts.

For future vehicle technologies, improvement in road load technologies benefits all powertrains, increasing fuel economy, as shown in Figure 2. Improvements are also achieved in engine break thermal efficiency and fuel cell peak efficiency, as summarized in Table 2.

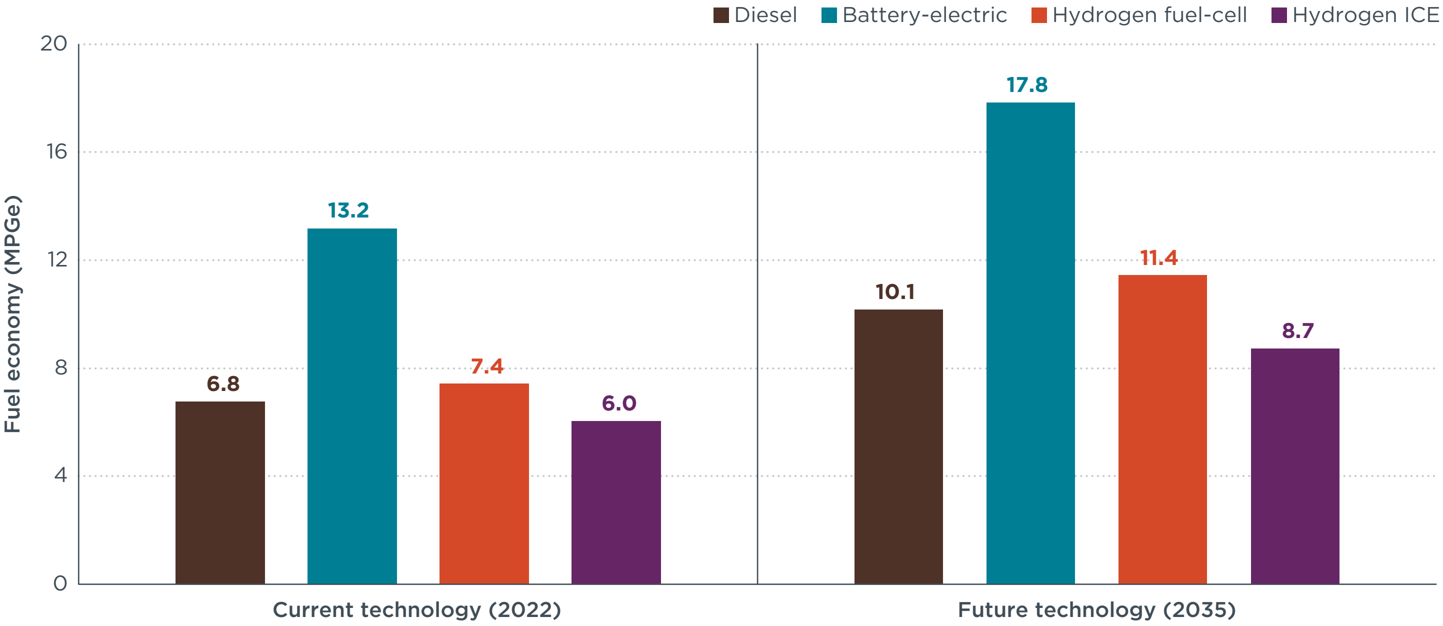


**Figure 2.** Summary of trucks' fuel economy for current and future vehicle technologies expressed in miles per diesel gallons equivalent, simulated under the NREL long-haul cycle and at reference payload of 38,000 lbs.

## PAYLOAD CAPACITY ESTIMATION

The payload capacity of each powertrain technology is calculated using a bottom-up approach. The weights of the main powertrain components are estimated based on a teardown analysis conducted by Ricardo Strategic Consulting on behalf of ICCT (Ricardo Strategic Consulting, 2022). All trucks share a common base glider, i.e., the same chassis and cab design. The base glider weight is 10,439 lb for current technologies in 2022, which is assumed to decrease to 8,638 lb due to chassis light weighting for future technologies. In addition, all trucks share the same trailer, weighing 13,500 lb for current technologies and decreasing to 10,850 lb for future technologies.

The powertrain and energy storage weights differ significantly among the four considered truck technologies, mainly driven by the truck's technical specifications. The battery electric and hydrogen fuel-cell tractor-trailer powertrain components and accessory weights are summarized in Table 3. The diesel truck powertrain componentry weight is estimated to be around 7,559 lb (Ricardo Strategic Consulting, 2022), and the hydrogen ICE truck powertrain componentry weight is estimated to be 6,959 lb,[1] excluding the hydrogen storage tanks.

---

[1] Assumed similar to CNG trucks. Numbers adopted from Hunter et al. (2021).

**Table 3.** Battery electric and hydrogen fuel-cell tractor-trailer powertrain components and accessory weights.

| Component | Specification | | Weight multiplier | |
|---|---|---|---|---|
| | Battery electric | Fuel cell | Current | Future |
| **Battery** | Varies by range | 70 kWh | 0.14 kWh/kg | 0.25 kWh/kg |
| **Fuel cell** | | 210 kW | 0.6 kW/kg | 0.6 kW/kg |
| **Hydrogen tank** | | Varies by range | 0.046 kg/kg | 0.046 kg/kg |
| **Electric drive** | 339 kW | | 0.4375 kW/kg | |
| **Power electronics** | 339 kW | | 3.6 kW/kg for battery electric<br>5 kW/kg for hydrogen fuel-cell | |
| **On-board charger** | 44 kW | 6.6 kW | 0.95 kW/kg for high power<br>1.12 kW/kg for low power | |
| **Air compressor** | 6 kW | | 0.087 kW/kg | |
| **Steering pump** | 9 kW | | 0.072 kW/kg | |
| **Air conditioning unit** | 10 kW | | 0.91 kW/kg | |
| **Heater** | 10 kW | | 1 kW/kg | |
| **Battery thermal management** | 339 kW | | 3.5 kW/kg for battery electric<br>7.14 kW/kg for hydrogen fuel-cell | |

*Note:* Data from Ricardo Strategic Consulting (2022) and Sharpe and Basma (2022)

Figure 3 shows the truck weight breakdown for the four considered powertrain technologies, highlighting the maximum truck payload capacity for current and future vehicle technologies. Hydrogen fuel-cell and hydrogen ICE powertrains show a similar payload capacity relative to their diesel counterparts, while battery electric trucks are expected to suffer from payload capacity losses of less than 20% relative to diesel for current vehicle technology. For future vehicle technologies, the truck battery size is expected to decrease due to energy efficiency improvement, battery energy density improvement, and the rollout of MW charging stations. This diminishes the payload capacity gap between battery electric and diesel trucks to less than 2%.

The payload capacity of current battery electric trucks under the considered truck specifications in this study is around 39,600 lb, which is higher than the 38,000 lb reference payload used in this study and defined by EPA's regulatory impact analysis of 2016. Therefore, we assume there will be no additional costs due to the payload losses for battery electric trucks in this study. The impact of higher truck payloads on the TCO analysis is examined in the sensitivity analysis section.

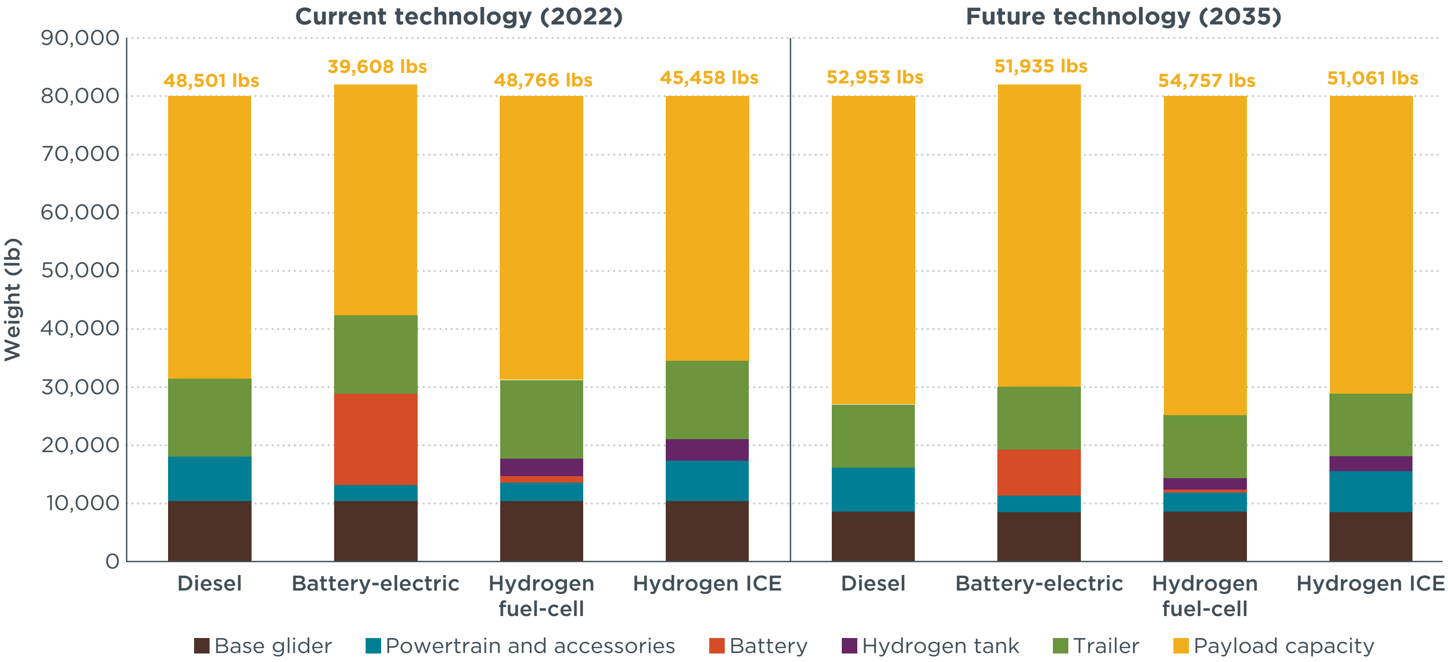


**Figure 3.** Weight breakdown for Class 8 sleeper cab long-haul trucks for different powertrain technologies. Battery size: 1 MWh for the current technology scenario and 740 kWh for the future technology scenario.

## TOTAL COST OF OWNERSHIP MODELING

This section explains the TCO modeling approach for the four considered truck technologies. The TCO model for battery electric trucks has been thoroughly described in previous ICCT publications (Basma, Saboori, & Rodríguez, 2021; Basma, Rodríguez, Hildermeier, & Jahn, 2022). The model for hydrogen fuel-cell trucks is described in Basma, Zhou, and Rodríguez (2022). The model converts all fixed and operational expenses of a particular model year truck into cash flows, considering the analysis period and discount rate. The TCO analysis includes the truck's purchase and finance cost, insurance, residual value, diesel fuel, hydrogen fuel, charging, labor, and maintenance costs. The analysis period is five years, which is considered representative of first ownership in the United States, and the discount rate is 7%.

### Capital expenses

The truck capital expenses include its retail price and the related financial costs, in addition to the truck residual value.

#### *Manufacturer suggested retail price*

The average manufacturer suggested retail price (MSRP) of a diesel Class 8 tractor in 2022, determined from several publicly available sources, is $158,000 (Slowik et al., 2023). We expect this cost to increase to $170,000 due to compliance with future emissions targets, assuming the diesel technology will reach its full potential by 2035 (Buysse, Sharpe, & Delgado, 2021). For the hydrogen ICE truck, we assume that the tractor cost, excluding the hydrogen tank, will be $3,000 less than its diesel equivalent, considering the diesel fuel tank and the simpler emission control systems.

We estimate MSRPs for the battery electric and hydrogen fuel-cell trucks using a bottom-up approach. First, the base glider cost, which includes the chassis and all powertrain accessories, is estimated based on the truck's technical specifications and the costs reported in Xie et al., (2023). The manufacturing costs of the main powertrain components are then estimated individually, including for the battery, fuel cell unit, hydrogen tanks, and electric drive. Table 4 summarizes these direct manufacturing costs. These costs are then aggregated to calculate the truck's direct manufacturing cost (DMC).

**Table 4.** Direct manufacturing costs of the main zero-emission truck components in 2022, 2030, and 2040.

| Parameter | 2022 | 2030 | 2040 |
|---|---|---|---|
| **Energy battery** | 230 $/kWh | 123 $/kWh | 99 $/kWh |
| **Power battery** | 408 $/kWh | 242 $/kWh | 194 $/kWh |
| **Fuel cell** | 826 $/kW | 301 $/kW | 242 $/kW |
| **Hydrogen tank** | 1,261 $/kg | 844 $/kg | 675 $/kg |
| **Electric drive** | 60 $/kW | 23 $/kW | 18 $/kW |

The truck's retail price is calculated by multiplying the DMC by indirect cost multipliers (ICMs) adopted from U.S. Environmental Protection Agency and U.S. Department of Transportation (2016) to account for costs related to research and development, overhead, marketing and distribution, warranty expenditures, and profit markups. In general, technologies with low maturity levels will incur high ICMs. We use ICMs of complexity level "High 1" for the base glider components and the battery pack.[2] For the fuel cell and hydrogen storage tank, ICM complexity level "High 2" is used.[3]

Figure 4 shows the MSRP evolution for the four considered powertrain technologies. The calculated retail prices consider the incentives provided in the Inflation Reduction Act for battery electric and hydrogen fuel-cell trucks (Inflation Reduction Act, 2022). These incentives, which expire in 2032, are calculated as 30% of the price differential between a zero-emission truck and its diesel equivalent, capped at $40,000. The truck retail price is assumed to be financed through loans with a 4% annual interest rate over five years.

---

[2] ICM Complexity level "High 1" corresponds to an ICM of 1.42 in 2022, which decreases linearly to 1.27 by 2035.

[3] ICM Complexity level "High 2" corresponds to an ICM of 1.53 in 2022, which decreases linearly to 1.27 by 2035.

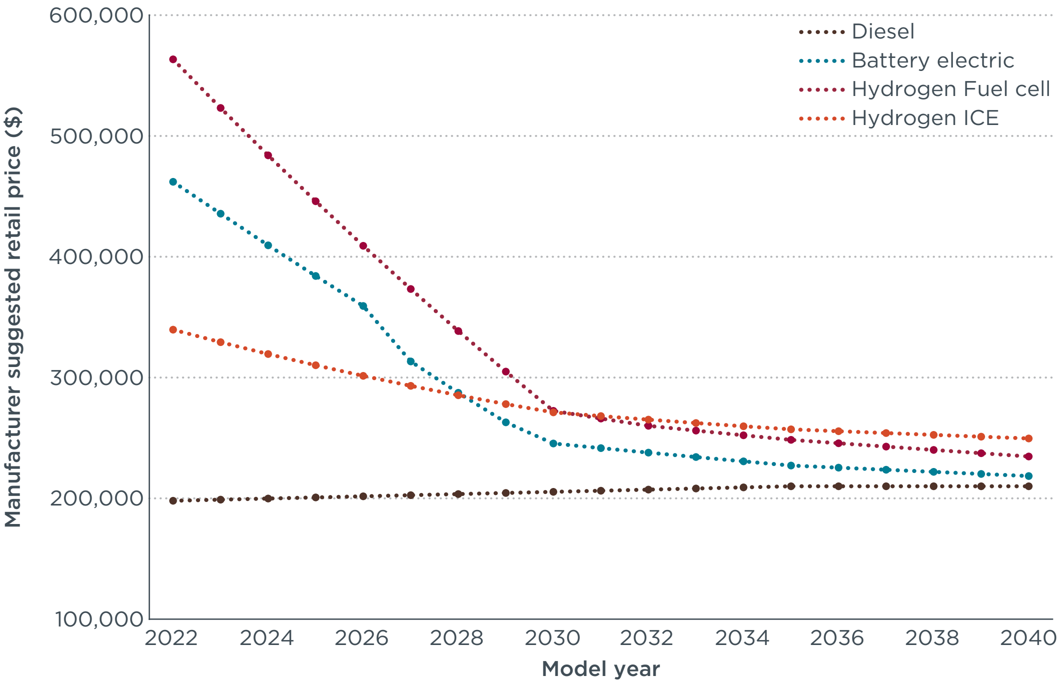


**Figure 4.** Retail price evolution of Class 8 long-haul tractor-trailers for diesel, battery electric, fuel-cell, and hydrogen internal combustion engine trucks between 2022 and 2040.

Fuel-cell trucks record the highest retail price in 2022, reaching $600k, primarily driven by the fuel cell unit and hydrogen tank cost, followed by the battery electric truck at around $500k. Hydrogen ICE trucks are almost $120k more expensive than their diesel counterparts due to the cost of the hydrogen tanks. The retail price of all alternative truck technologies decreases between 2022 and 2040, driven by cost reduction in main zero-emission powertrain components, such as batteries, fuel cells, and hydrogen tanks. The diesel truck retail price is expected to increase due to the more expensive needed technology packages needed to comply with future emissions standards, assuming that diesel technology will reach its full potential by 2035.

The estimated battery electric truck retail price shows a significant drop between 2026 and 2027, driven by our assumption that MW charging coverage in the United States by 2027 will be large enough so that manufacturers will size batteries considering the possibility of charging during the day, which results in smaller battery sizes and lower retail prices as discussed earlier. A detailed price breakdown can be found in Xie et al. (2023).

### *Residual value*

The truck residual value at the end of the analysis period is estimated using similar methodology as in Basma, Zhou, and Rodríguez (2022) and Mao et al. (2021). For diesel trucks, depreciation is composed of a fixed annual depreciation rate of 7.5% and a variable depreciation rate as a function of the vehicle miles travelled and the truck lifetime. We assume the truck's lifetime is 15 years with a total cumulative VMT of ~ 1.3 million miles (United States Environmental Protection Agency, 2022). After operating for five years and covering a cumulative VMT of ~ 600,000 miles, the estimated truck residual value is 35%.

Alternative truck technologies include components with a potential second-life market, such as batteries, fuel cells, and hydrogen tanks. Current fuel cell durability is estimated to be around 15,000 hours of operation, which increases to 22,000 hours by 2030 (Ricardo Strategic Consulting, 2022). The fuel cell residual value is estimated based on the number of operating hours after five years. This results in a 25% fuel cell unit residual value for 2022 technology and 49% residual value by 2030. The battery lifetime is assumed to be 3,000 cycles in 2022, with the potential to increase to 5,000 cycles in the future (Nykvist & Olsson, 2021). The number of charge-discharge cycles per day depends on the charging power. Given our assumption that trucks today will primarily rely on 350 kW chargers during the day, the daily number of cycles is 1.25, resulting in 2,000 cycles after 5 years. When MW chargers are used as of 2027, the number of daily cycles will increase to 1.8, resulting in ~ 2,900 cycles after 5 years. We also assume that battery residual value at its end life, defined as 80% capacity retention, will be 15% of its original price (Burke & Zhao, 2017). That being said, for current battery and charging technologies, the estimated battery residual value is ~ 43%, increasing to 49% for future battery technologies. Hydrogen storage tanks are assumed to have a lifetime of 5,000 charge/discharge cycles (Pohl & Ridell, 2019), resulting in a 70% residual value after five years of operation. Table 5 summarizes the residual value assumptions.

**Table 5.** Residual value of components after five years of operation

| Component | 2022 Model year | 2030 Model year |
|---|---|---|
| **Base glider and e-drive** | 35% | 35% |
| **Battery** | 43% | 49% |
| **Fuel cell** | 25% | 49% |
| **Hydrogen tank** | 70% | 70% |

### *Federal excise tax*

The retail sale of commercial vehicles is subject to a 12% federal excise tax (Office of the Federal Register, 2012). This implies that trucks with a higher MSRP will be subject to a higher federal excise tax.

## Operational expenses

Operational expenses are related to the vehicle miles driven, including the costs of diesel fuel, hydrogen fuel, charging, maintenance, and labor.

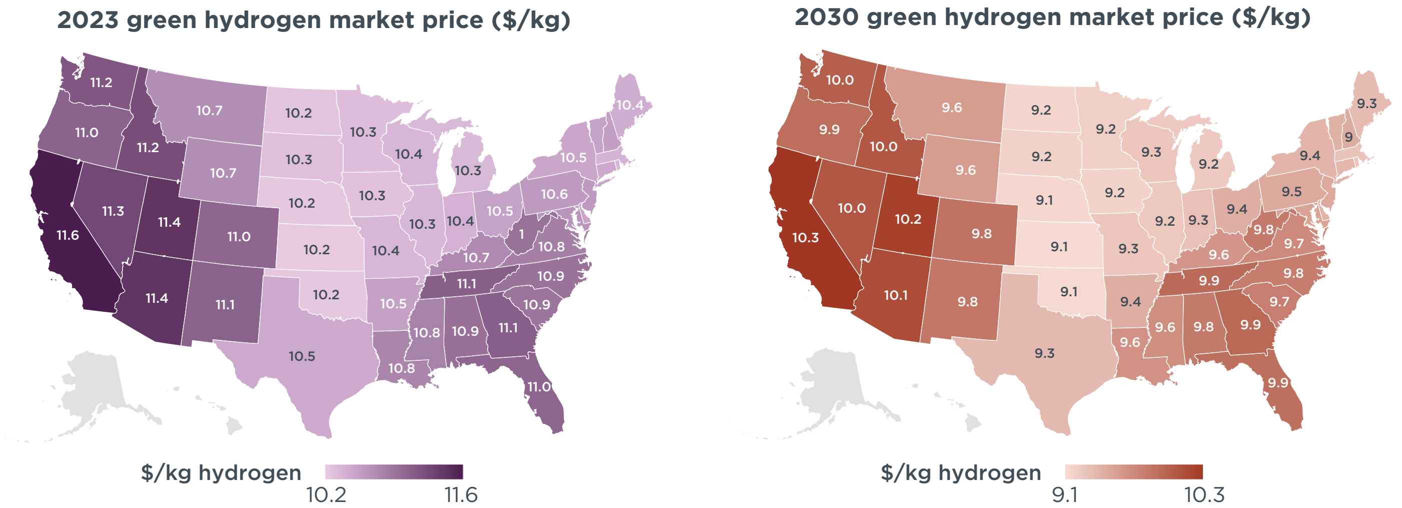
### *Diesel fuel price*

The price of diesel fuel in the United States differs among regions and states. Data from the U.S. Energy Information Administration categorizes diesel fuel prices based on geographic areas (U.S. Energy Information Administration, 2022b). Projecting these prices into the future incurs a very high level of uncertainty. To account for this uncertainty, we assume several scenarios for the diesel fuel price evolution, presented in the results section, with the baseline scenario being the 2022 average prices.

It is worth highlighting that diesel fuel prices have almost doubled between 2020 and 2022, driven by the global energy crisis. In addition, diesel fuel prices are as low as $4.70/gal in the Gulf Coast states, while California records the highest prices exceeding $6.00/gal, 28% higher than the U.S. national average.

### *Hydrogen fuel price*

Hydrogen fuel prices across the U.S. states are taken from Slowik et al. (2023), where all detailed modeling methodology and data assumptions can be found. The prices include on-site renewable (green) hydrogen production costs, hydrogen refueling station costs, and tax credits for renewable electricity and clean hydrogen provided by the Inflation Reduction Act. Figure 5 shows the state-level green hydrogen price between 2023 and 2045 used in this study. Price variations across states result from varying solar and wind resources. States with more abundant solar or wind resources can run renewable electricity plants more often, achieving lower renewable electricity costs. Green hydrogen prices are expected to decrease over time as the technology matures.



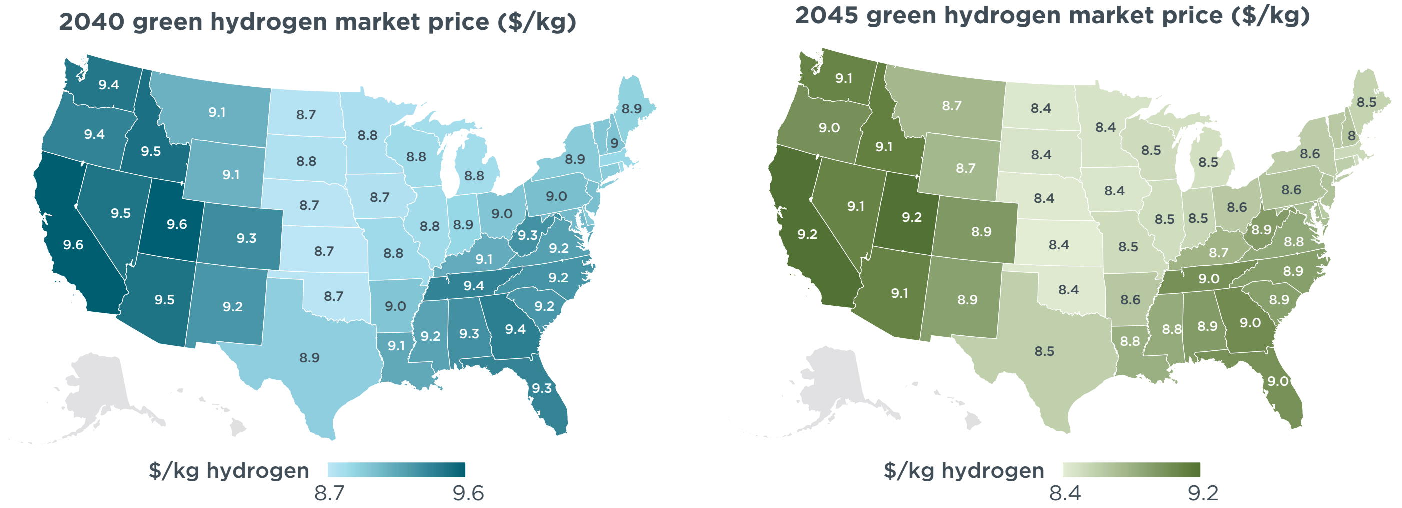


**Figure 5.** Summary of green hydrogen fuel market price at the pump in different states in 2023, 2030, 2040, and 2045.

### *Charging cost*

Charging cost is comprised of the electricity cost and the cost of the charging infrastructure. Electricity costs vary among and within states depending on local electricity tariffs and rates set by the respective utilities. Infrastructure costs are assumed to be independent of the charging station location and correspond to public on-route charging stations at truck stops along highways. Figure 6 shows the charging cost modeling framework.

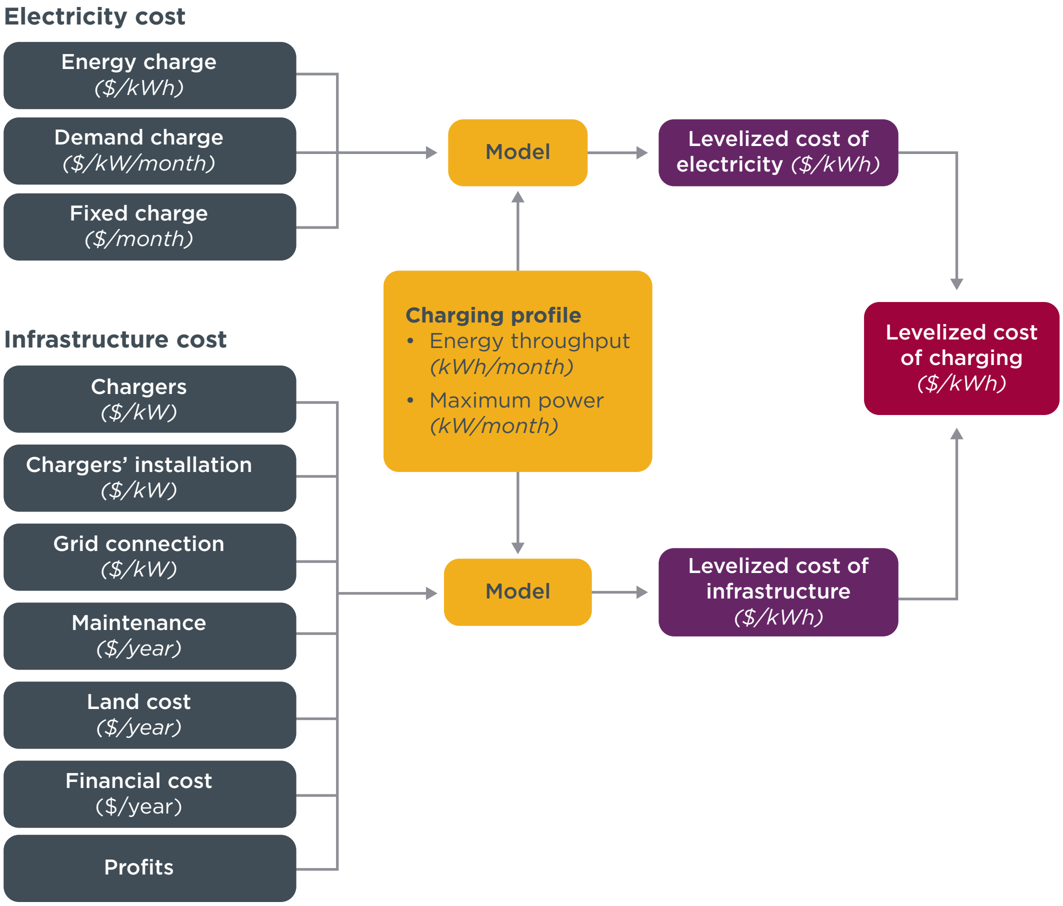


**Figure 6.** Charging cost modelling framework

We assume long-haul trucks will utilize on-route public charging stations at truck stops along highways. We assume a charging station size of 20 MW, including 17 1-MW chargers and 20 150-kW chargers. The charging station peak power demand is assumed to be 50% of the station size, considering the coincident load of MW charging events, as explained in Bennett et al. (2022). This peak demand drives grid upgrade costs and electricity demand charges.

Charging station utilization is dependent on the market uptake of battery electric trucks in the United States. We assume that the long-term utilization rate of on-route public charging stations is 15% by 2035, assuming utilization will increase linearly until 2035 in an approach similar to Bennett et al. (2022). The station utilization rate will directly impact the levelized cost of charging, as detailed in the proceeding sections.

### *Levelized cost of electricity*

Electricity costs are estimated for each of the seven representative states using cost information from the largest utilities in each state and those covering long-haul routes.

Table 6 summarizes the electricity rates considered in the selected states and the corresponding levelized cost of electricity.

**Table 6.** Summary of electricity rates considered in selected states.

| State | Source | Rate | Energy charge ($ cents/kWh) | Demand charge ($/kW/month) | Fixed charge ($/month) | Levelized cost of electricity (¢/kWh) |
|---|---|---|---|---|---|---|
| **California** | Pacific Gas and Electric Company (2022) | BEV-2-P rate (Primary distribution > 100 kW) | 19.57 [a] | - | 17,196 [b] | 20.48 |
| **Florida** | Florida Power and Light (2023) | General Service Large Demand Sheet 8.412 | 1.68 | 13.57 | 255 | 8.84 |
| **Georgia** | Georgia Power (2022) | Power & Light Large Schedule PLL-13 | Levelized cost provided by utility | | | 13.1 |
| **Illinois** | Billing sample estimate- Commonwealth Edison (2023) | Extra-large load (above 10 MW) | 6.53 [c] | 11.17 | 1,962 | 12.51 |
| **New York** | Billing sample estimate - National Grid (2023) | SC3 General – Primary service | 4.63 | 14.08 | 2,583 | 12.18 |
| **Texas** | Oncor (2022) | Primary - > 10 kW substation | 3.5 [d] | 8.3 [e] | - | 7.87 |
| **Washington** | Puget Sound Energy (2022) | Schedule 31 | 5.6 | 9.94 [f] | 358 | 10.85 |

a) There are three time-of-use energy charges: (1) peak (4p-9p) at 39.046 cents/kWh, (2) off-peak (9p-9a, 2p-4p) at 18.158 cents/kWh, and (3) super off-peak (9a-2p) at 15.892 cents/kWh. We assume 60% of charging will occur during off-peak hours, 10% during peak hours, and 30% during super off-peak hours.
b) Subscription charge at $85.98 per 50 kW block assuming 10 MW peak site capacity.
c) All state and municipal taxes are added to an energy charge of 3.5 cents/kWh, assumed based on the historic 5-year average.
d) Assumption based on a 5-year historic average.
e) aggregates demand and distribution charges.
f) Average between a summer tariff at 7.94 $/kW and a winter tariff at 11.94 $/kW.

### *Levelized cost of infrastructure*

Infrastructure cost includes the grid connection, charger, and the station's operational expenses. Figure 7 illustrates the major components of the battery electric truck charging infrastructure ecosystem. The grid connection costs include all expenses incurred in front of the meter, in addition to on-site transformers, electric panels, and switchgear.

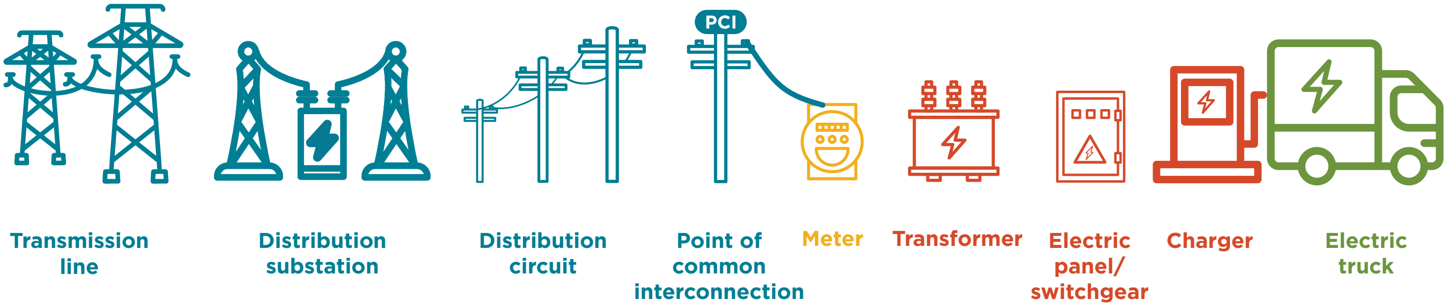


**Figure 7.** Battery electric truck charging infrastructure ecosystem.

The grid connection cost can add significant cost to the investment needed to deploy public MW charging stations. The underlying assumptions for our grid connection cost estimates are summarized below:

- There will be flexibility in choosing the station locations to reduce grid connection costs. We assume that there will either be sufficient space inside the existing substation to add another substation transformer or it will be possible to upgrade an existing substation transformer. Thus, the land costs for a new substation were not included in the infrastructure cost calculations, as well as the engineering, design, right-of-way acquisition activities (time), and costs.
- The station is connected to the primary voltage grid. Large charging hubs will most probably buy power from the utility at primary voltage.
- There is no onsite energy storage system to help reduce the peak load. Onsite energy storage batteries incur high investment costs. On the other hand, such technology can lower the charging station operational expenses related to demand charges and/or deal with the utility's inability to alleviate grid congestion.
- There is no renewable power generation at this public charging site.
- The charging station will incur all grid connection and upgrade costs.

Based on those underlying assumptions, Table 7 summarizes the grid connection, upgrade, the charger installation costs. These costs are developed based on utility experts' feedback for the 10 MW peak load charging site. The levelized cost is calculated assuming that all the mentioned components have a lifetime of 40 years. All costs are converted into annual cashflows considering an 8% internal rate of return.

**Table 7.** Summary of grid upgrade and connection costs, and charger's-related costs behind the meter.

| Component | Category | Notes | Cost | Levelized cost (¢/kWh) |
|---|---|---|---|---|
| **Sub-transmission line** | Sub-transmission | 115 kV line – Not included – Assumed the existing substation has sufficient space to accommodate another transformer, or a larger capacity substitute transformer. | - | - |
| **Greenfield substation** | Substation | Not included – Assuming the existing substation has sufficient space to accommodate another transformer. | - | - |
| **Substation transformer addition** | | One 28 MVA transformers added to an existing distribution substation. Cost Includes foundation, grounding, conduit and wiring, supply and install. | $2,000,000 | 0.74 |
| **Other equipment** | | Feeders, tie, transfer switches | $1,100,000 | 0.40 |
| **Distribution feeder** to the closest point on the grid (Point of Interconnection) | Distribution | Assuming an overhead distribution feeder, 1 mile in length. | $900,000 | 0.33 |
| **Connection to the meter**: closest point on the grid to a utility meter | To-the-meter | Assuming 300-feet long connection | $100,000 | 0.04 |
| **Utility meter** and meter base | | Primary service metering | $15,000 | 0.01 |
| **Primary Transformer** (converting 13kV to 480V) | Behind-the-meter | 1,500 kVA – Assumed 10 1500kVA transformers to meet a 10 MW peak demand, with some redundancy for maintenance, futureproofing, and to meet electrical safety/code requirements. | $600,000 | 0.22 |
| **Charger installation** | | Includes switchgear, wiring, onsite construction, and trenching. Assumed $195,000 per 1 MW charger (total 17) and $137,250 per 150 kW charger (total 20) | $6,060,000 | 2.23 |
| **Total** | | | **$10,775,000** | **3.97** |

Table 8 summarizes the costs for the chargers and charging station, which are adopted from Bennett et al. (2022). The levelized cost is calculated assuming the chargers have a lifetime of 10 years. All these cost components are converted into annual cashflows considering an 8% internal rate of return.

**Table 8.** Summary of charger and station operation costs. Adopted from Bennett et al. (2022).

| Component | Costs | Levelized cost (¢/kWh) |
|---|---|---|
| **Charger acquisition** | 1 MW charger: $300,000 per charger (Total 17)<br>150 kW charger: $53,655 per charger (Total 20) | 4.04 |
| **Annual maintenance per charger** | $3,200 per charger (Total 37) | 0.52 |
| **Annual land cost** | $25,000 for 1 acre | 0.11 |
| **Total** | | **4.67** |

The total charging cost is the sum of electricity and infrastructure levelized costs, as summarized in Figure 8. This is the estimated average levelized cost of charging over the station's lifetime. In other words, although we expect lower utilization rates during the early years of operation, we assume that charging station operators will average their expenses and profits over the station's lifetime.

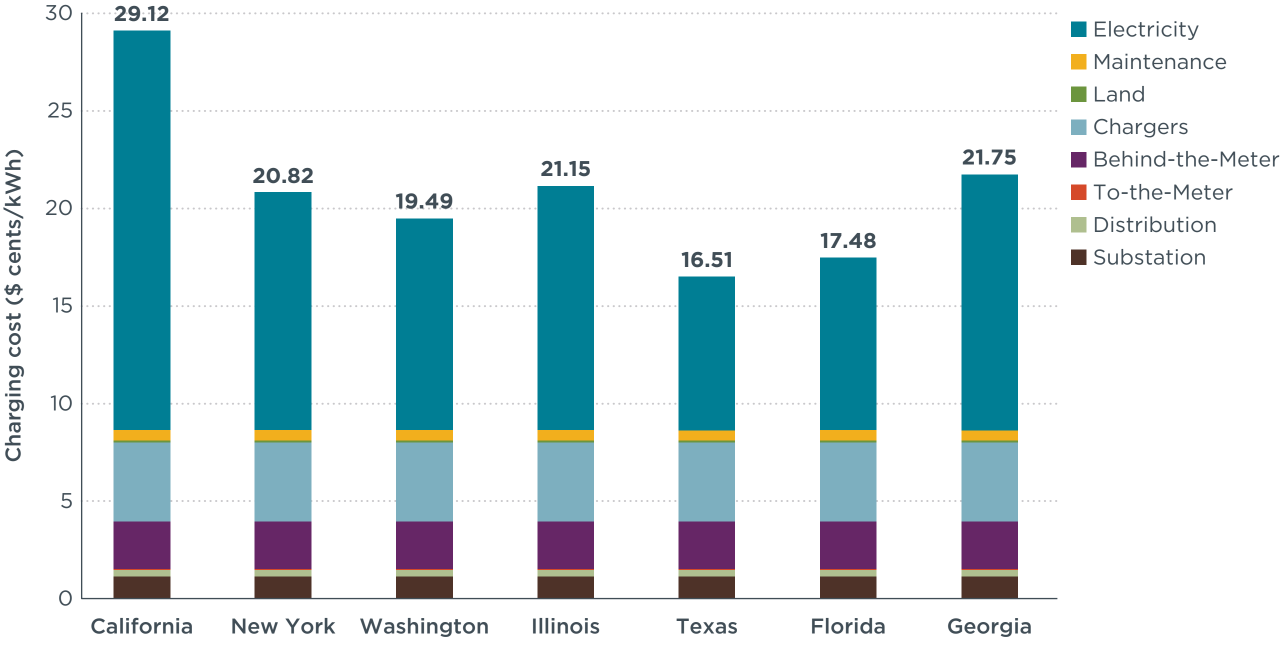


**Figure 8.** Charging costs in selected states. Data correspond to 2022–2023 electricity rates in each state.

*Maintenance cost*

Maintenance costs for diesel, battery electric, and hydrogen fuel-cell Class 8 long-haul trucks are adopted from a recent publication by UC Davis (Wang et al., 2022). Figure 9 shows the truck maintenance costs breakdown for the different powertrain technologies. Maintenance costs include common components among all powertrain technologies, such as brakes, gears, air conditioning, tires, and cabin air filters. Powertrain-specific components, such as engine-related maintenance, battery, fuel cell, and hydrogen storage, are also highlighted. Hydrogen ICE trucks are assumed to have similar maintenance costs to their diesel counterparts, with additional costs related to the maintenance of the hydrogen storage system.

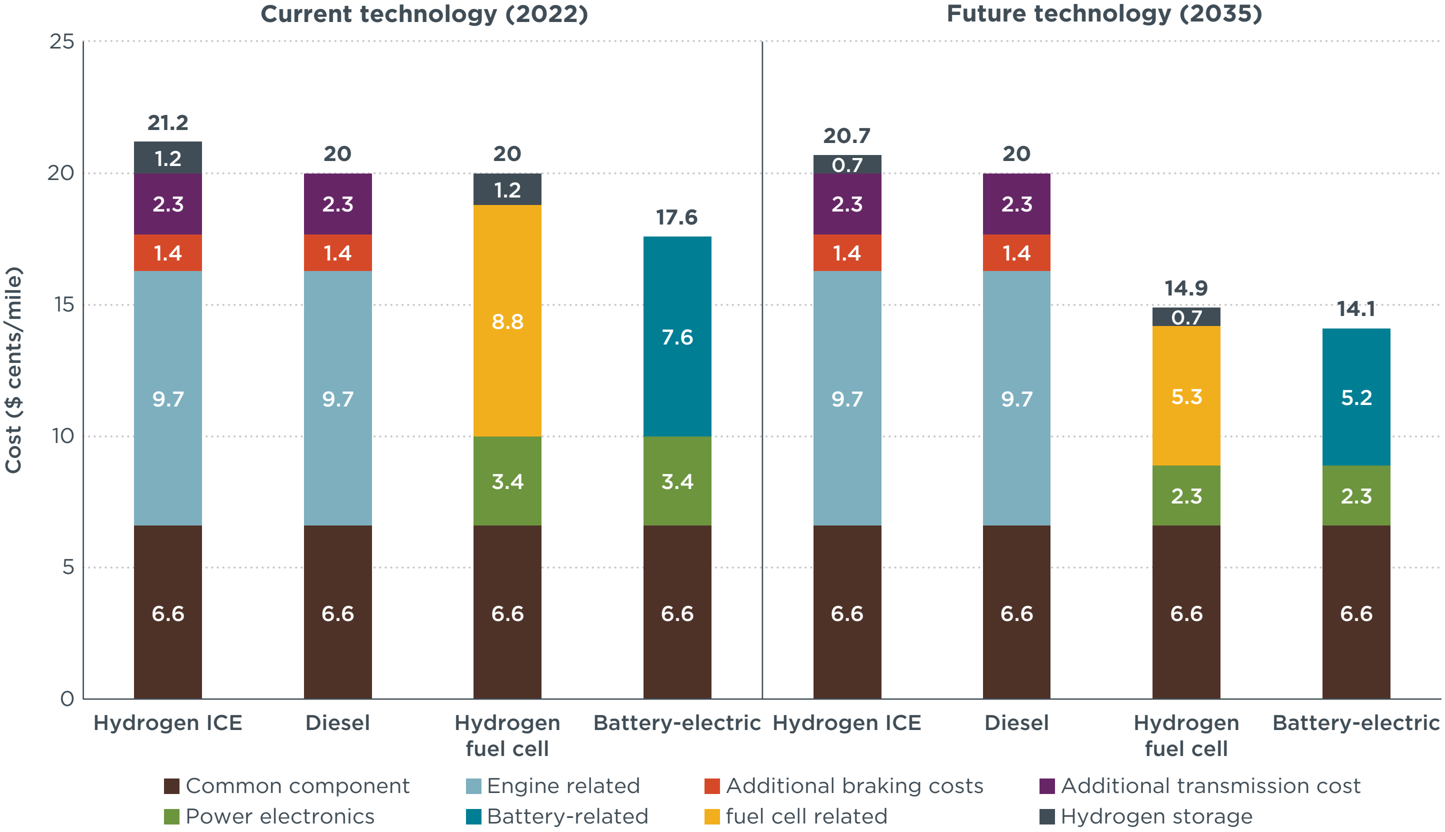


**Figure 9.** Maintenance costs breakdown for different powertrain technologies for Class 8 long-haul trucks in the United States. Adopted from Wang et al. (2022).

For current vehicle technology, battery electric trucks record the lowest maintenance costs at $0.176/mi, relative to $0.20/mi–$0.212/mi for other technologies. With the expected development in battery and fuel cell technologies over time, associated maintenance costs are expected to decrease to around $0.14/mi–$0.15/mi by 2035 due to the learning curve effect for new technologies.

### *Labor cost*

Labor costs are estimated on a per-mile basis assuming a rate of $0.79 per mile, according to Burnham et al. (2021). For battery electric trucks, drivers may need to stop more frequently to recharge, increasing their number of working hours during the day. This is the case for battery electric trucks before the wide deployment of MW charging stations along long-haul routes prior to 2027. The additional labor cost is calculated depending on the additional number of working hours due to truck charging. Prior to the deployment of MW chargers, this can lead to a 10%–15% increase in labor cost.

### *Insurance*

Insurance costs for tractor-trailers can be a significant TCO component. This study considers comprehensive and collision insurance in addition to liability insurance. The former is an annual cost estimated to be around 3% of the truck purchase price, and the latter is calculated as a fixed per-mile cost at $0.065/mi, similar to Burnham et al. (2021). This approach distinguishes between different powertrain technologies with different retail prices, and also distinguishes between different truck annual VMT.

## NATIONAL ANALYSIS: MONTE CARLO SIMULATIONS

The TCO analysis at the U.S. national level is carried out using a stochastic Monte Carlo approach, given the significant variation in several TCO cost components among different states, primarily diesel, hydrogen, and charging costs. In addition, the analysis captures the reported variations in the technology cost, such as for the battery, fuel cell, and hydrogen tanks. Table 9 summarizes the stochastic variables' mean and standard deviation data used to develop the respective probability density functions. Figure 10 illustrates the probability density functions for the different stochastic variables used in the Monte Carlo analysis. We assume that all variables will follow a lognormal distribution.

All technology cost data are available in a recent ICCT publication (Xie et al., 2023), where we collect data from different sources and estimate the sample mean and standard deviation per component. We rely on the state-specific data presented earlier in the operational expenses section for hydrogen fuel, diesel fuel, and charging cost data. We define weights to the different state-specific cost data based on the percent distribution of tractor-trailer vehicle's miles traveled, as shown in Figure A1 in the appendix. We then estimate each stochastic variable's weighted average mean and standard deviation. Diesel and hydrogen fuel price data are collected for all 50 states, while charging costs are only developed for the 7 states considered in this paper, assuming they cover a wide spectrum of charging costs in the United States. Another important stochastic variable to define is the vehicle's daily mileage, which will drive the vehicle energy storage size, mainly the battery energy storage capacity. Variation in daily mileage is also considered, where we define a "mileage variability" variable used in the vehicle energy storage sizing.

**Table 9.** Summary of stochastic variables used to develop the respective probability density functions.

| Variable | Mean | | | Standard deviation | | |
|---|---|---|---|---|---|---|
| | 2022 | 2030 | 2040 | 2022 | 2030 | 2040 |
| **Energy battery cost ($/kWh)** | 232 | 123 | 99 | 53.4 | 22.6 | 7 |
| **Power battery cost ($/kWh)** | 409 | 242 | 198 | 123 | 63 | 15 |
| **Fuel cell cost ($/kW)** | 827 | 301 | 241 | 502 | 191 | 70 |
| **Hydrogen tank cost ($/kg)** | 1,262 | 844 | 675 | 313 | 224 | 120 |
| **Electric drive cost ($/kW)** | 60 | 23 | 18 | 9 | 4.1 | 2 |
| **Diesel fuel price ($/gal)** | 4.13 | | | 2.95 | | |
| **Charging cost ($ cents/kWh)** | 19.6 | | | 3.2 | | |
| **Green hydrogen price ($/kg)** | 11.2 | 9.58 | 9.08 | 0.4 | 0.35 | 0.29 |
| **Daily driving mileage (miles)** | 400 | | | 75 | | |
| **Daily mileage variability** | 1.1 | | | 0.1 | | |

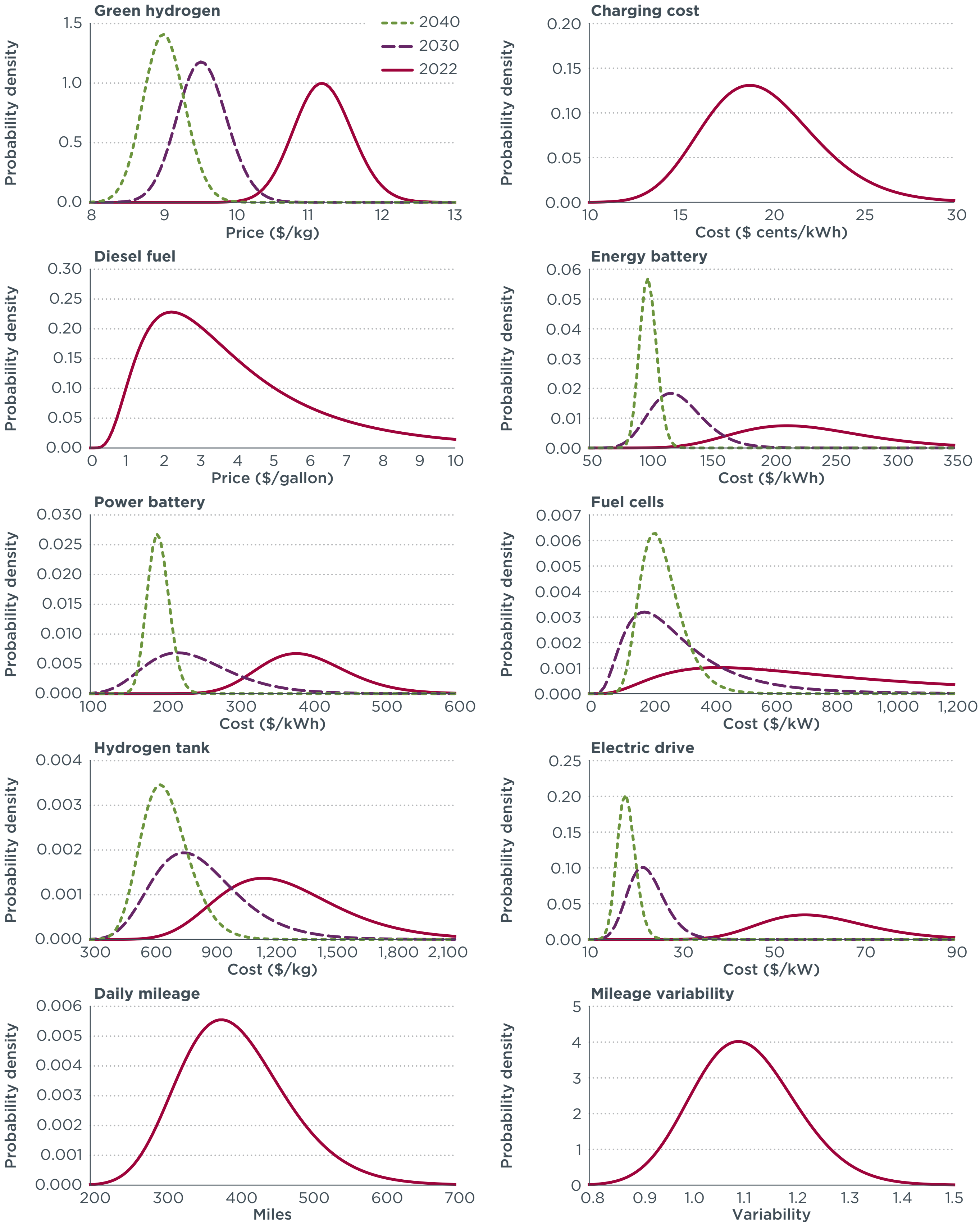


**Figure 10.** Summary of probability density functions for the different stochastic variables used in the Monte Carlo analysis.

# RESULTS AND DISCUSSION

## STATE-SPECIFIC ANALYSIS

This section presents the state-specific TCO, considering the average capital expenses and the state-specific fuel and energy prices presented earlier. We consider that diesel and charging costs are fixed between 2022 and 2040 due to the high uncertainty in predicting the diesel and electricity cost evolution during this timeframe. The impact of diesel fuel and charging cost variations on the TCO are examined in the sensitivity analysis section. Hydrogen fuel prices are assumed to vary between 2022 and 2040, as discussed previously.

Figure 11 shows the state-specific TCO for all technologies for truck model year 2022. Across all states, diesel trucks are the cheapest to operate, as their TCO ranges from $1.88/mi (Texas) to $2.06/mi (California). The highest TCO for diesel trucks is recorded in California due to the high diesel fuel prices there. Battery electric trucks come as the second cheapest technology from a TCO perspective. The lowest TCO for battery electric trucks is recorded in Texas at $2.18/mi, driven by the low charging costs, while battery electric trucks operating in California record the highest TCO at $2.50/mi. Battery electric trucks generally record a 13% to 26% higher TCO than their diesel counterparts in 2022.

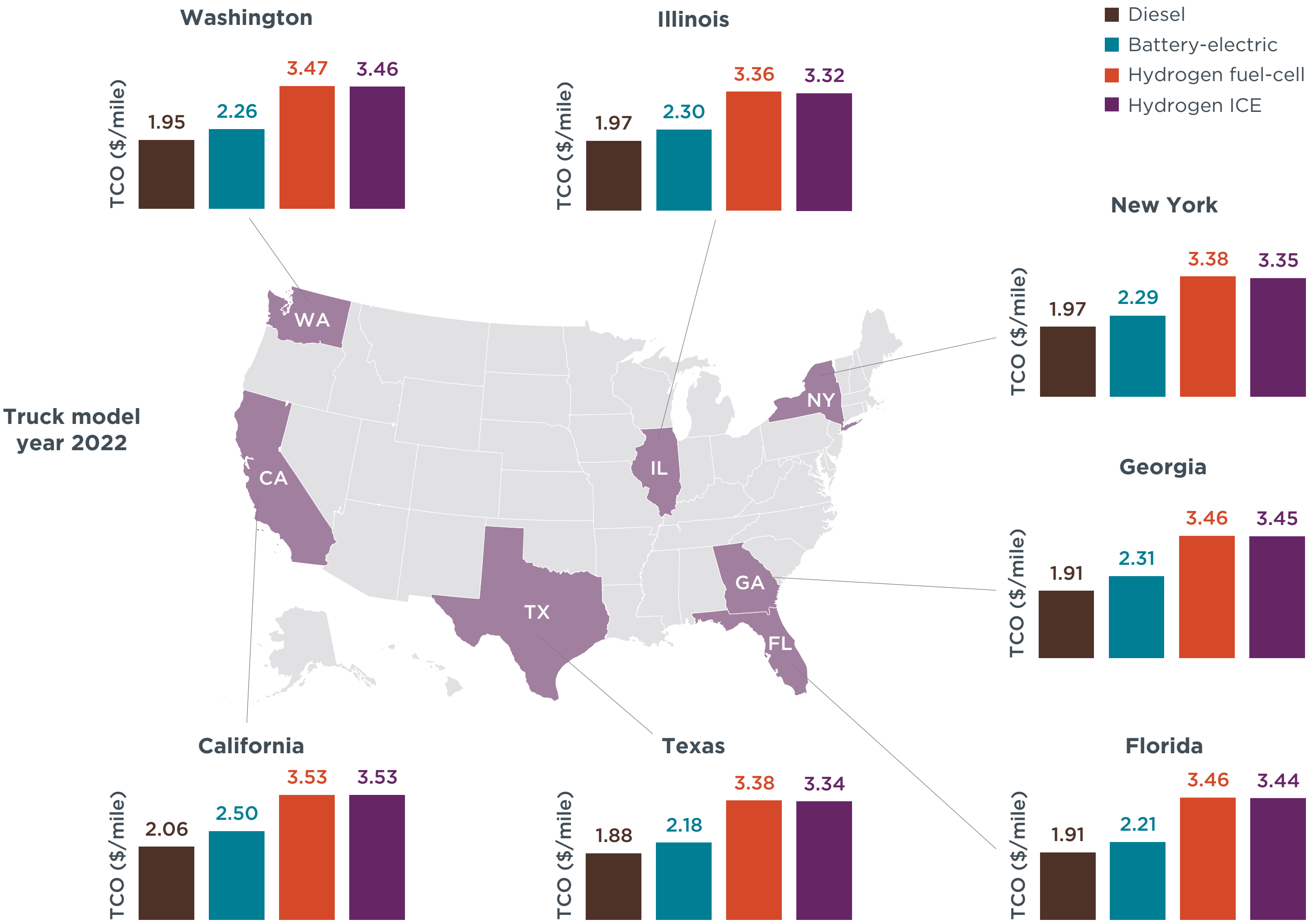


**Figure 11.** State-specific total cost of ownership for different truck technologies. Case of truck MY 2022.

Hydrogen fuel-cell and hydrogen ICE trucks show a very similar TCO for MY 2022, reaching as high as $3.53/mi for trucks operating in California and as low as $3.36/mi for trucks operating in Illinois. This is mainly driven by the green hydrogen fuel price in each state, which are expected to be the highest in California and the lowest in Illinois. Both hydrogen-powered trucks record a 68%–81% higher TCO than diesel trucks and 34%–59% higher TCO than their battery electric counterparts.

Figure 12 shows the state-specific TCO for all technologies for truck MY 2030. In all considered states, battery electric trucks are expected to record the lowest TCO, ranging from $1.63/mi (Texas) to $1.90/mi (California). Diesel trucks follow with the second lowest TCO, ranging between $1.76/mi and $1.91/mi. For MY 2030 trucks, battery electric trucks are expected to record a 3%–8% lower TCO than diesel trucks. The TCO analysis for MY 2040 trucks is presented in Figure A9 in the appendix.

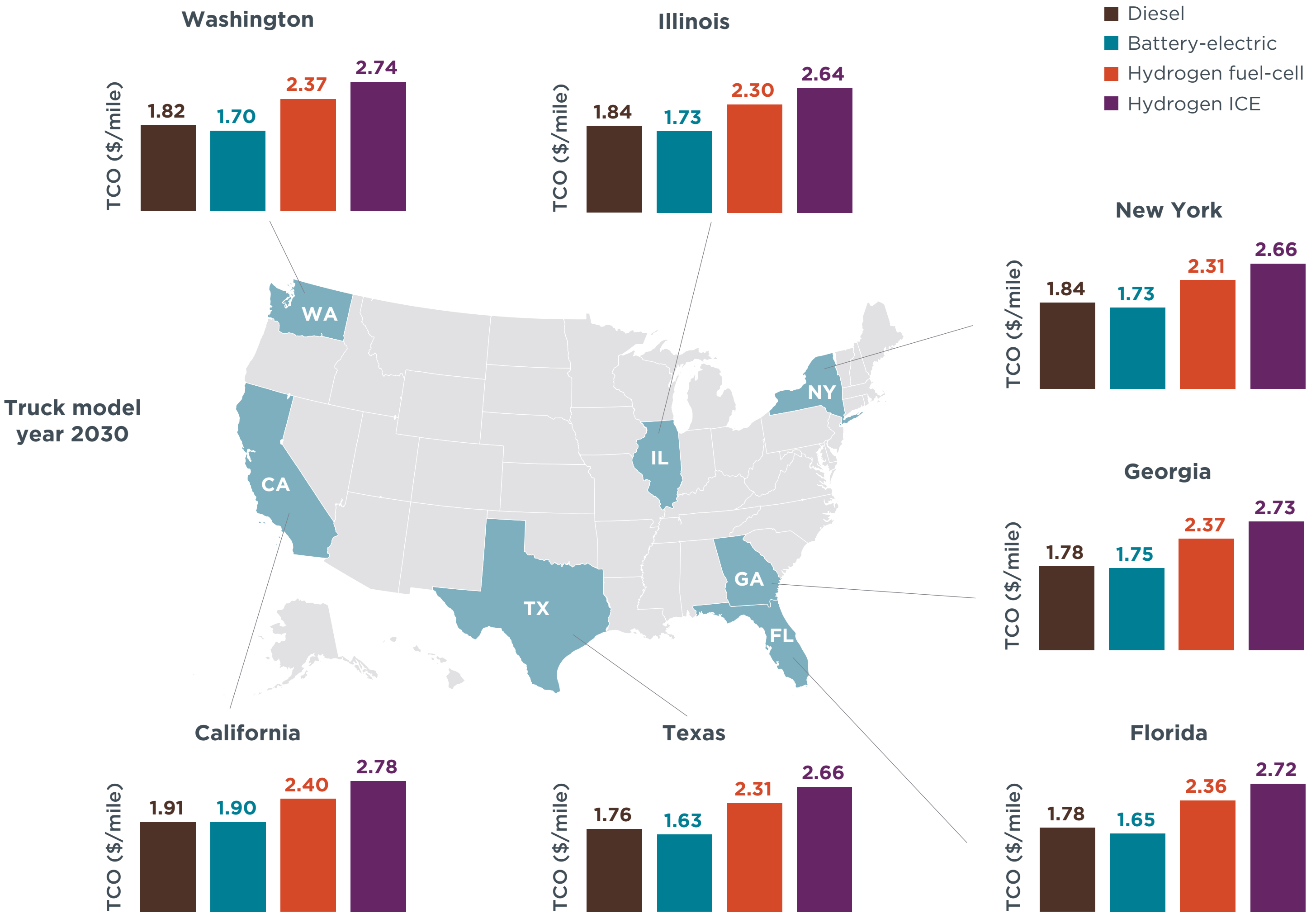


**Figure 12.** State-specific total cost of ownership for different MY 2030 truck technologies.

The TCO of hydrogen fuel-cell trucks is expected to remain much higher than their diesel and battery electric counterparts but lower than that of hydrogen ICE trucks. Hydrogen fuel-cell trucks record a TCO in the range of $2.30/mi to $2.40/mi, while the TCO of hydrogen ICE trucks ranges from $2.64/mi to $2.78/mi, or almost 20% higher than the TCO of hydrogen fuel-cell trucks.

Table 10 summarises the year of TCO parity of alternative truck technologies relative to diesel trucks in selected states.

**Table 10.** Summary of TCO parity year between alternative truck technologies and diesel trucks in selected states.

| Technology | California | Florida | Georgia | Illinois | New York | Texas | Washington |
|---|---|---|---|---|---|---|---|
| **Battery electric** | 2030 | 2028 | 2029 | 2028 | 2028 | 2027 | 2028 |
| **Hydrogen fuel-cell** | > 2040 | > 2040 | > 2040 | > 2040 | > 2040 | > 2040 | > 2040 |
| **Hydrogen ICE** | > 2040 | > 2040 | > 2040 | > 2040 | > 2040 | > 2040 | > 2040 |

The TCO findings for MY 2040 trucks and the detailed state specific TCO breakdown are documented in the appendix.

## SENSITIVITY ANALYSIS

The previous state-specific analysis uses the 2022 average diesel fuel prices in selected states and 2022 electricity rates. It assumes these prices and costs will remain fixed during the entire analysis period between 2022 and 2040. However, energy and fuel prices are subject to continuous variations, and this section examines the impact of these prices on the TCO of different truck technologies. This section also examines the impact of truck payload on the TCO analysis.

### Impact of fuel and energy prices

Figure 13 shows the TCO parity sensitivity to diesel fuel prices and charging costs. The inclined lines represent the TCO parity year between both truck technologies. The sensitivity analysis covers a wide range of fuel prices, where diesel fuel prices are varied between $2.00/gal and $7.50/gal, representing the minimum and maximum prices observed in the United States between 2017 and 2022. Charging cost is varied between $0.10/kWh and $0.35/kWh. For example, if the diesel fuel price is $5.00/gal and the charging cost is $0.20/kWh, TCO parity between battery electric and diesel trucks is expected between 2027 and 2028.

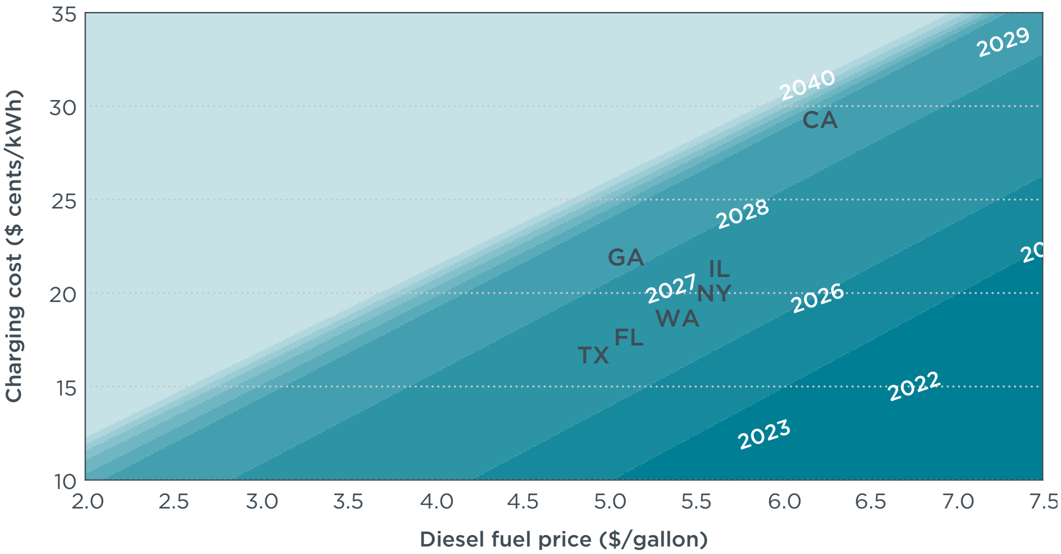


**Figure 13.** Total cost of ownership parity sensitivity to diesel fuel prices and charging costs. A comparison between battery electric and diesel.

Variations in diesel fuel prices and charging costs significantly impact the year battery electric trucks achieve TCO parity with diesel trucks. For the current range of diesel fuel prices in the United States of between $4.00/gal and $6.00/gal, and the range of charging costs between $0.15/kWh and $0.30/kWh, battery electric trucks can achieve TCO parity with diesel trucks by the end of this decade.

Figure 14 shows the TCO parity sensitivity to diesel and hydrogen fuel prices. The inclined lines represent the TCO parity year between both truck technologies. Hydrogen fuel price is varied between $2.00/kg and $12.00/kg. The higher limit considers the maximum modeled green hydrogen fuel price between 2022 and 2040. The lower limit is a hypothetical figure to model a highly favorable green hydrogen fuel price.

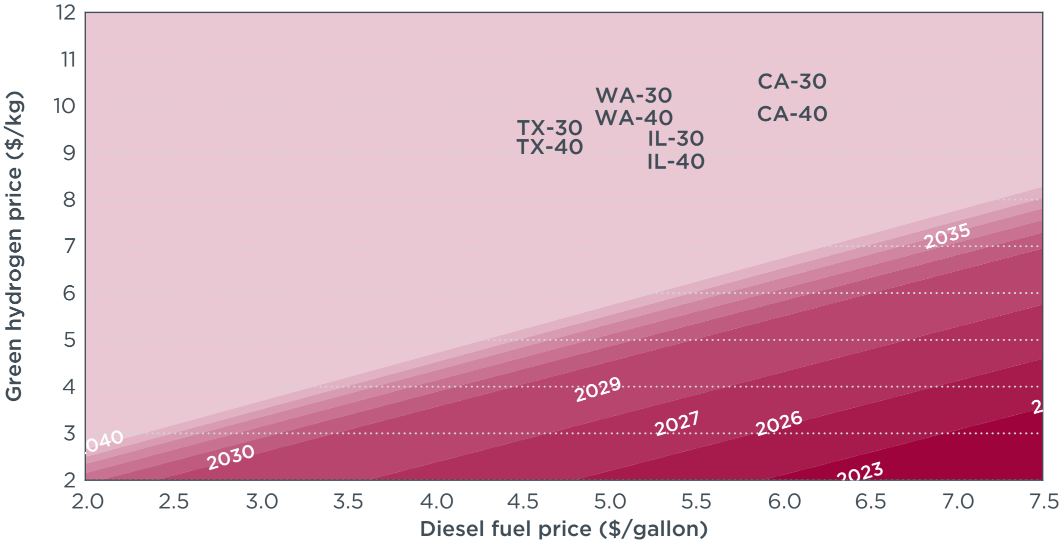


**Figure 14.** Total cost of ownership parity sensitivity to diesel and hydrogen fuel prices. A comparison between hydrogen fuel-cell and diesel trucks.

Variations in diesel and green hydrogen fuel prices significantly impact the TCO parity year between fuel-cell and diesel long-haul trucks. Fuel-cell long-haul trucks may achieve TCO parity with diesel trucks by 2025 if diesel fuel prices exceed $6.00/gal and green hydrogen fuel price drops below $5.00/kg. The figure highlights the current diesel fuel prices and the expected green hydrogen fuel price in 2030 and 2040 in selected states, ranging between $8.50/kg and $10.50/kg. Under the current diesel fuel prices, if fuel-cell trucks are to achieve TCO parity with diesel trucks by 2030, green hydrogen fuel prices would need to be between $4.00/kg and $6.00/kg. By 2040, the break-even hydrogen price is in the range of $5.00/kg to $7.00/kg.

Figure 15 shows the hydrogen ICE and diesel TCO parity sensitivity to diesel and hydrogen fuel prices. Hydrogen ICE trucks operating in long-haul are unlikely to reach TCO parity with diesel trucks any time before 2040 unless extreme scenarios result in very high diesel fuel prices exceeding $5.00/gal and very low green hydrogen fuel prices below $3.00/kg.

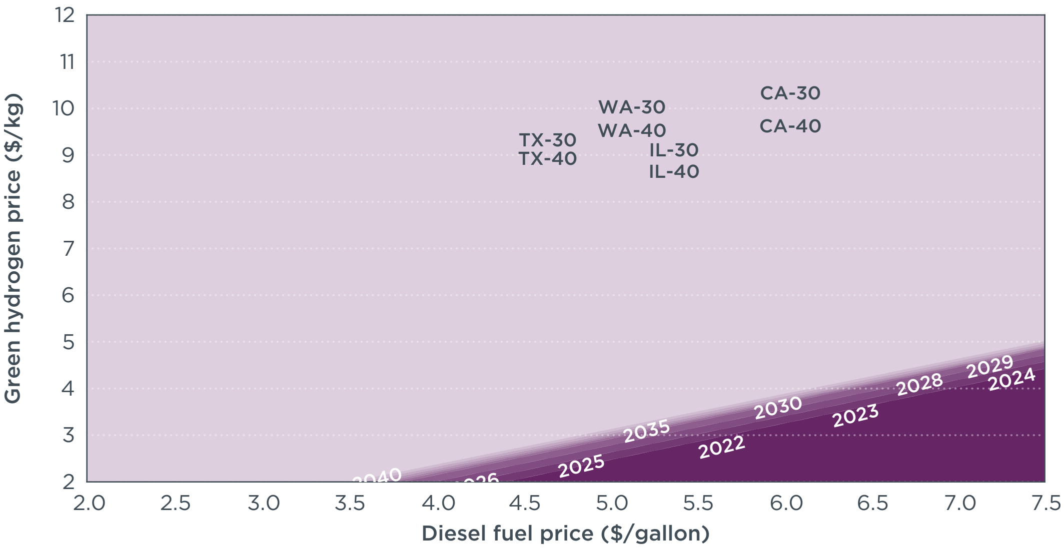
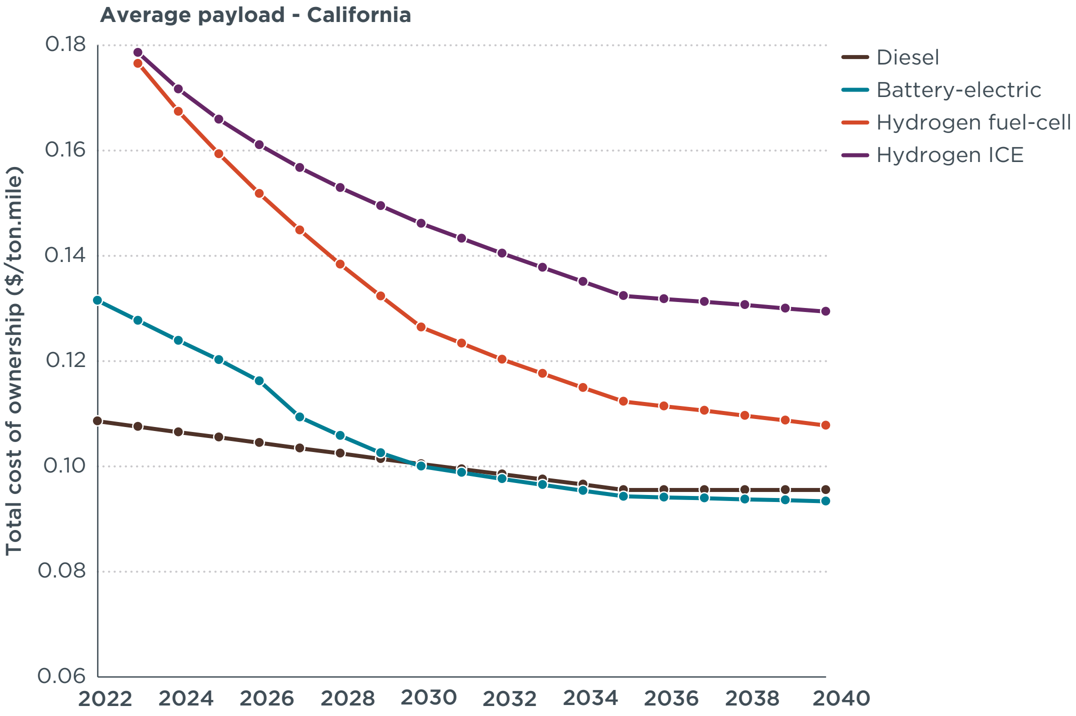


**Figure 15.** Total cost of ownership parity sensitivity to diesel and hydrogen fuel prices. A comparison between hydrogen ICE and diesel trucks.

### *Impact of payload*

The average payload of the truck and its payload capacity can significantly affect its economic viability. The average use case presented in this study assumes an average payload of 38,000 lb, which is below the payload capacity of all considered powertrain technologies. This section examines the impact of operating at full payload on the TCO of the different trucks. However, as shown earlier, different truck powertrain technologies will have different payload capacities. To be able to compare the TCO for different maximum payloads, we calculate the TCO of each truck technology in $/ton. mi, i.e., dividing the TCO by the maximum payload capacity of each truck, expressed in U.S. tons.

With higher payloads, the fuel consumption of each truck technology increases, which yields higher fuel and energy costs. More energy-efficient powertrains will be less sensitive to this increase in payload. On the other hand, trucks with higher payload capacities can realize lower TCO per ton. Figure 16 shows the TCO for different technologies at average and maximum payloads. The TCO parity between battery electric and diesel trucks will be delayed by three to four years for the case of maximum payload compared to the case of average payload. The TCO gap between battery electric and both hydrogen-powered trucks will also be narrower, but their TCO would still be higher than that of their diesel and battery electric counterparts.



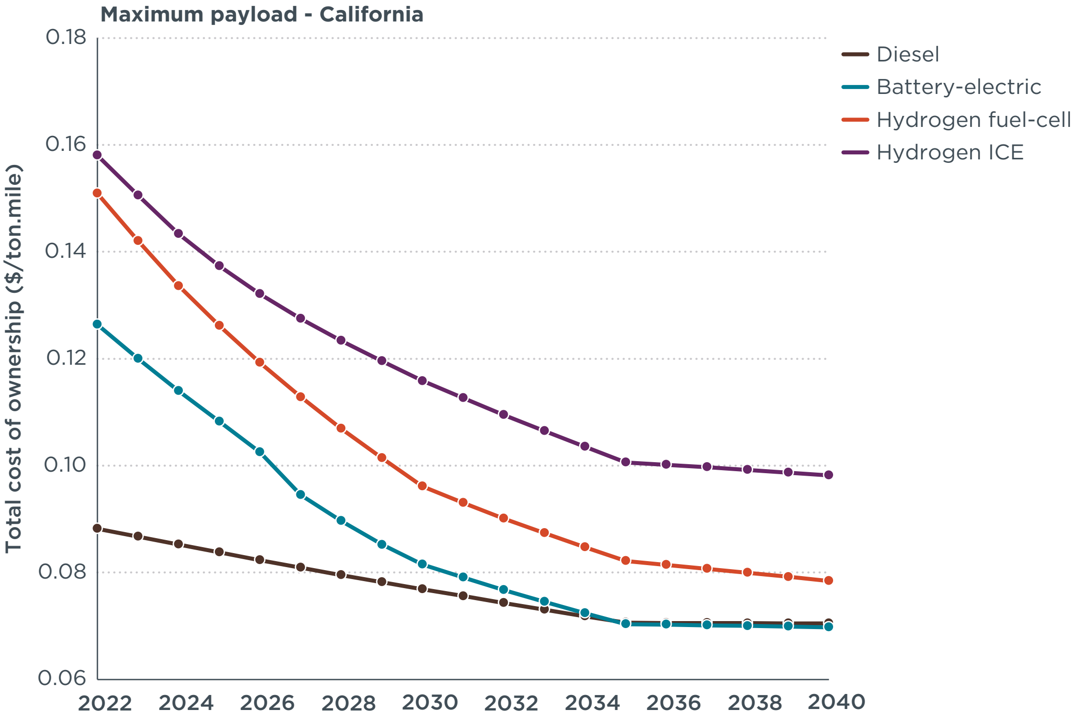


**Figure 16.** TCO of different truck technologies at average and maximum payloads.

### TCO of battery electric versus hydrogen fuel cell trucks

Both battery electric and hydrogen fuel-cell trucks are zero-emission powertrain technologies at the tailpipe level and have the potential to achieve significant GHG emission savings relative to diesel trucks from a lifecycle perspective. As both technologies share a similar environmental performance, their future market uptake in the long-haul segment is expected to be driven by their economic performance, namely their TCO.

Figure 17 shows the TCO parity sensitivity of battery electric and hydrogen fuel-cell trucks to charging costs and green hydrogen fuel prices for several model years. For MY 2023 trucks, given the expected charging cost range of between $0.15 /kWh and $0.30/kWh, the break-even green hydrogen price is in the range of $2.00/kg–$5.00/kg, which is much lower than the $10.00/kg–$12.00/kg estimated price range in 2023. Even under very pessimistic charging cost assumptions of $0.50/kWh, the required break-even green hydrogen price is $8.50/kg, which is still lower than the estimated price range in 2023.

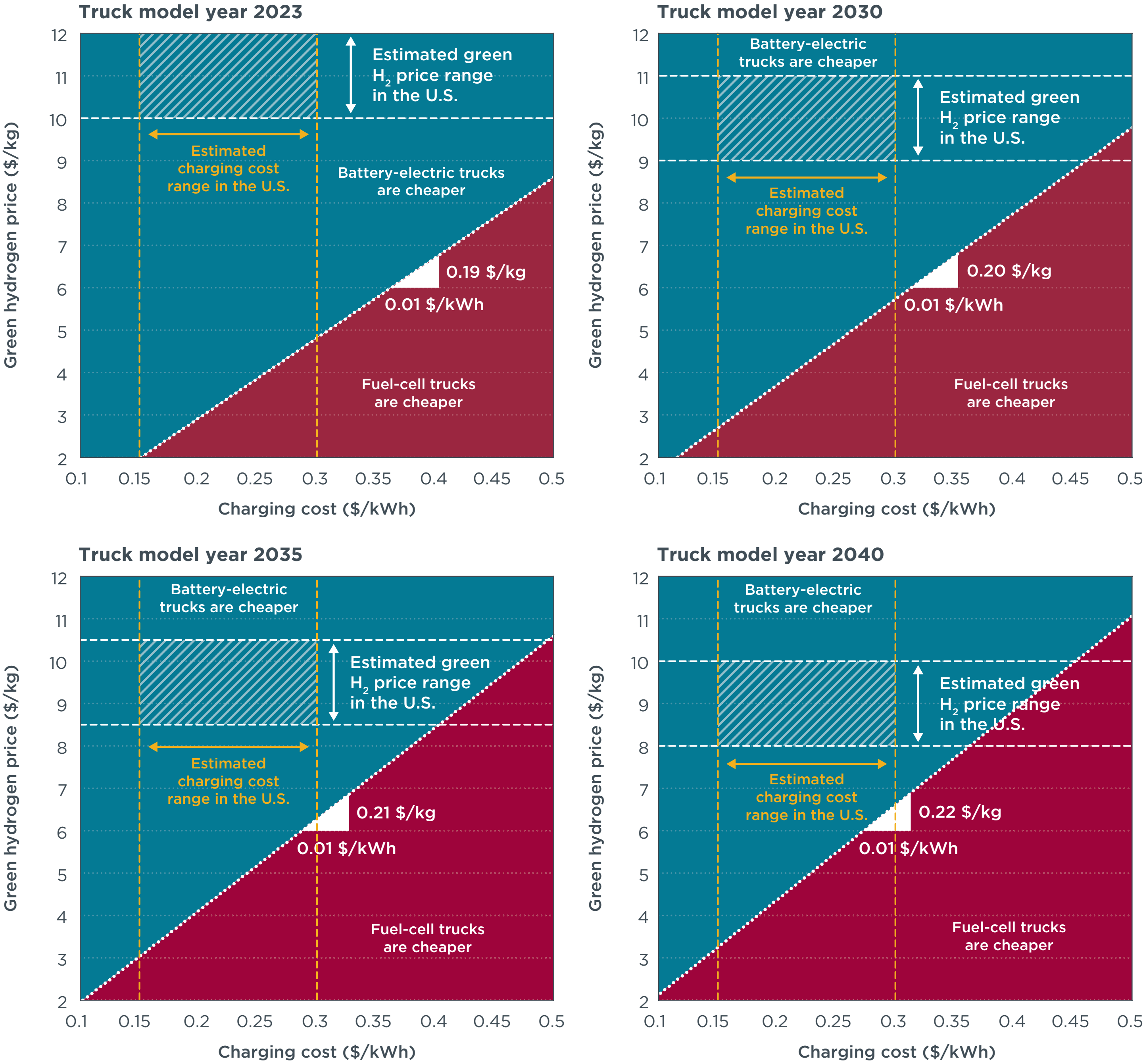


**Figure 17.** Total cost of ownership parity sensitivity to charging costs and hydrogen fuel prices for several truck model years. A comparison between battery electric and hydrogen fuel cell.

As the fuel-cell truck technology becomes more mature over time, the break-even hydrogen prices slightly increase, as shown in the panels of Figure 17 representing different truck model years. For MY 2040 trucks, given the expected charging cost range of between $0.15 /kWh and $0.30/kWh, the break-even green hydrogen price ranges from $3.50/kg to $7.00/kg, which is still lower than the $8.00/kg–$10.00/kg estimated price range in 2022.

Under the current and future estimates for green hydrogen prices, fuel-cell trucks can achieve a better TCO than their battery electric counterparts as of 2035 only if charging costs exceed $0.45/kWh, which is much higher than the modelled charging costs in this study. Nonetheless, this might be the case for some states or regions that are not considered in this study.

It is worth mentioning how TCO parity is more sensitive to variations in hydrogen fuel prices than charging costs, as implied by the triangle slopes in Figure 17. This is primarily related to the fuel economy, as battery electric trucks are more energy-efficient and consume less per mile than hydrogen fuel-cell trucks.

### TCO of hydrogen fuel cell versus hydrogen ICE trucks

Figure 18 shows the TCO parity between both hydrogen-powered trucks as a function of the truck model year, highlighting the break-even hydrogen fuel price point per model year. In general, hydrogen ICE trucks incur a lower MSRP than their hydrogen fuel cell rivals. On the other hand, hydrogen fuel cell trucks have shown better fuel economy, as presented earlier in Figure 2. In cases of low hydrogen fuel prices, hydrogen ICE trucks are expected to have a better TCO because their operational expenses are not high enough to diminish their MSRP gap with hydrogen fuel cell trucks.

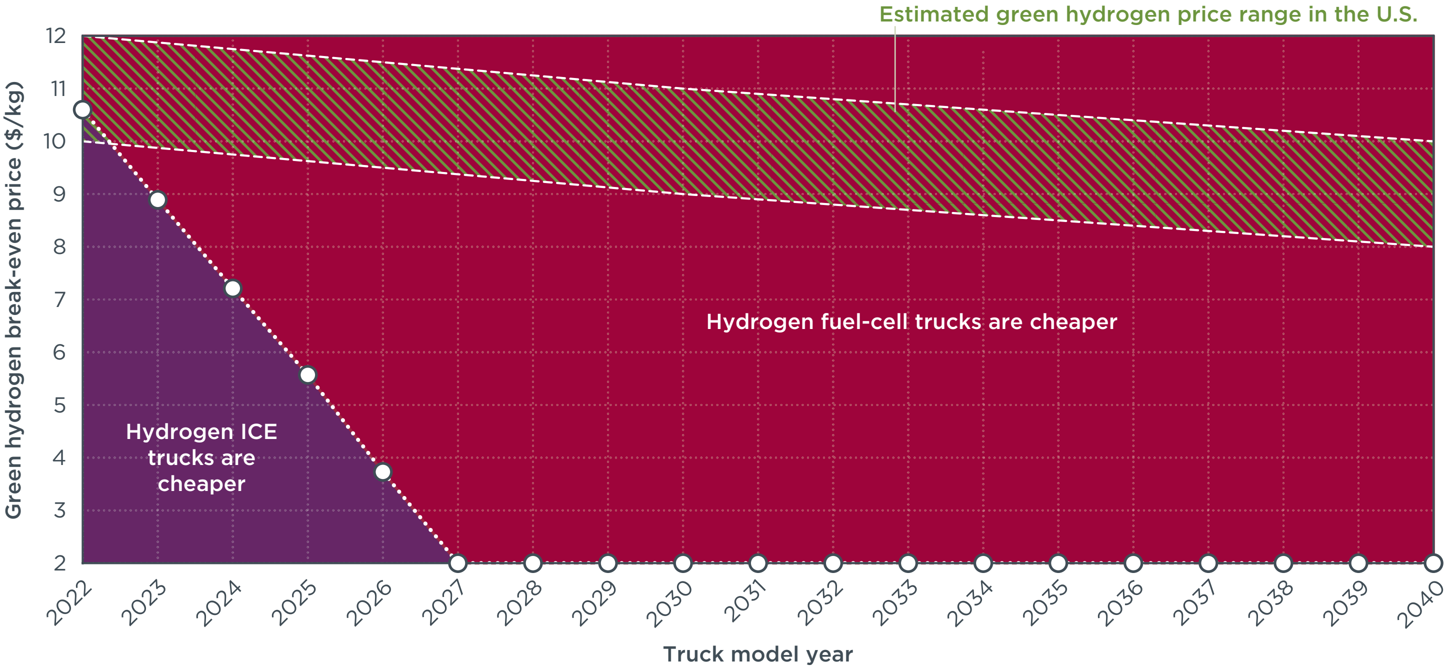


**Figure 18.** Total cost of ownership parity sensitivity to hydrogen fuel prices from 2022 to 2040. A comparison between hydrogen fuel-cell and hydrogen ICE trucks.

During the early market uptake phase, when fuel-cell truck MSRP is expected to be the highest, the break-even hydrogen fuel price is around $10.50/kg in 2022. In other words, if green hydrogen fuel price at the pump is below 10.5 $/kg, hydrogen ICE trucks will have a lower TCO. The hydrogen break-even price decreases over time as the hydrogen fuel-cell truck MSRP decreases, closing the gap with hydrogen ICE trucks. By 2025, the hydrogen break-even price between both hydrogen-powered technologies will be around $5.70/kg. As of 2027, the break-even price will be very low, reaching unlikely hydrogen prices below $2.00/kg.

Hydrogen ICE trucks may have a better TCO than hydrogen fuel-cell trucks in the short term if hydrogen fuel prices are low enough. However, when fuel-cell technology costs decrease in the long term, hydrogen fuel-cell trucks are expected to have a better TCO even for very low hydrogen fuel prices.

## NATIONAL ANALYSIS

The stochastic analysis is conducted considering the inputs presented in Table 9. The analysis quantifies the percentage of cases where a certain technology will achieve the lowest TCO for a given truck model year. Figure 19 shows the split between the different considered truck technologies between 2022 and 2040 based on their TCO. The split is determined based on a Monte Carlo sample size of 10,000. For truck model year 2022, diesel truck is recognized as the technology with the lowest TCO for more than 95% of the cases, followed by battery electric trucks for the remaining 5%. For future truck model years, the percentage of cases where battery electric trucks record the lowest TCO increases continuously, reaching 70% by 2030 and 85% by 2040. This behavior is related to the reduction in the truck's MSRP and improved fuel economy over time, which reduces the operational expenses of battery electric trucks. It is worth highlighting the steep jump from model year 2026 to 2027. This is related to our assumption that MW charging stations will be available with wide coverage as of 2027, allowing long-haul trucks to be equipped with smaller batteries, which reduces their MSRP. Beyond 2030, the increase becomes less steep, driven by the slower reduction in the battery electric truck's retail price.

Both hydrogen-powered trucks are not recognized as the cheapest truck technology in any truck model year, mainly due to the high green hydrogen fuel price.

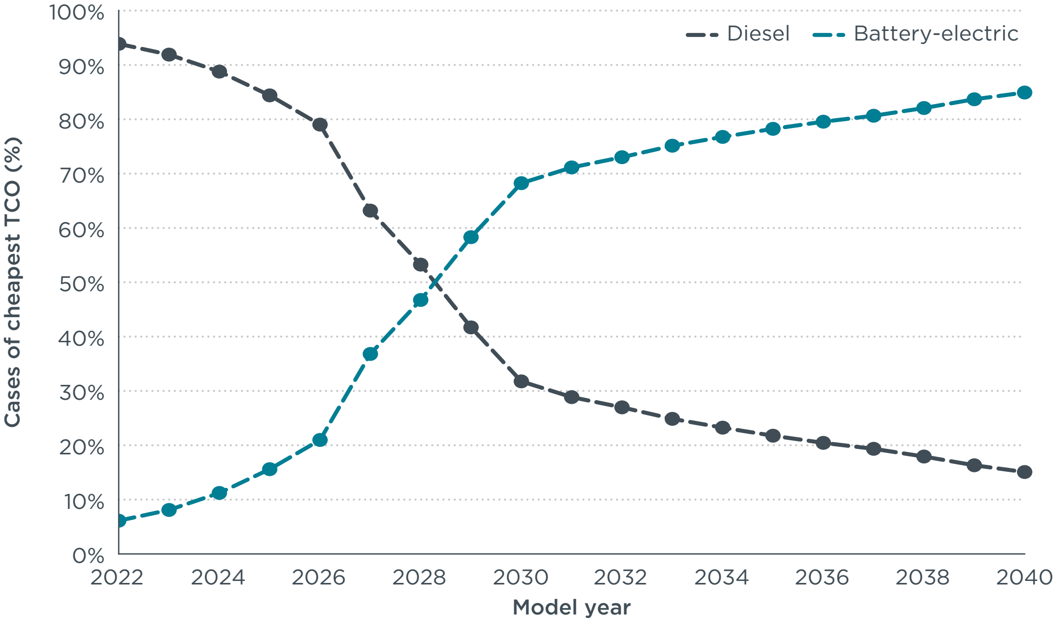


**Figure 19.** Split among different truck technologies between 2022 and 2040 based on TCO. The share of both hydrogen-powered trucks is 0%.

Battery size will have a significant impact on the TCO parity between battery electric and diesel trucks. A required battery size is affected by several factors, mainly the daily truck mileage and available charging technology. While the average daily truck mileage is a representative metric in the TCO calculation, truck operators will most likely size their batteries considering the worst-case scenario for the daily mileage needs, which could be significantly higher than the average daily mileage. This is captured in the truck daily mileage variability, which corresponds to the maximum variation in the truck's day-to-day average daily miles covered. For example, a daily mileage variability of 10% implies that the maximum number of daily miles covered by a truck is 10% higher than its average daily mileage.

Figure 20 shows the impact of the truck's average daily mileage and the daily mileage variability on its economic viability compared to diesel trucks. The figure corresponds to truck model year 2040 and for the national average diesel and charging costs. The battery design point is the product of the truck's average daily mileage and mileage variability.

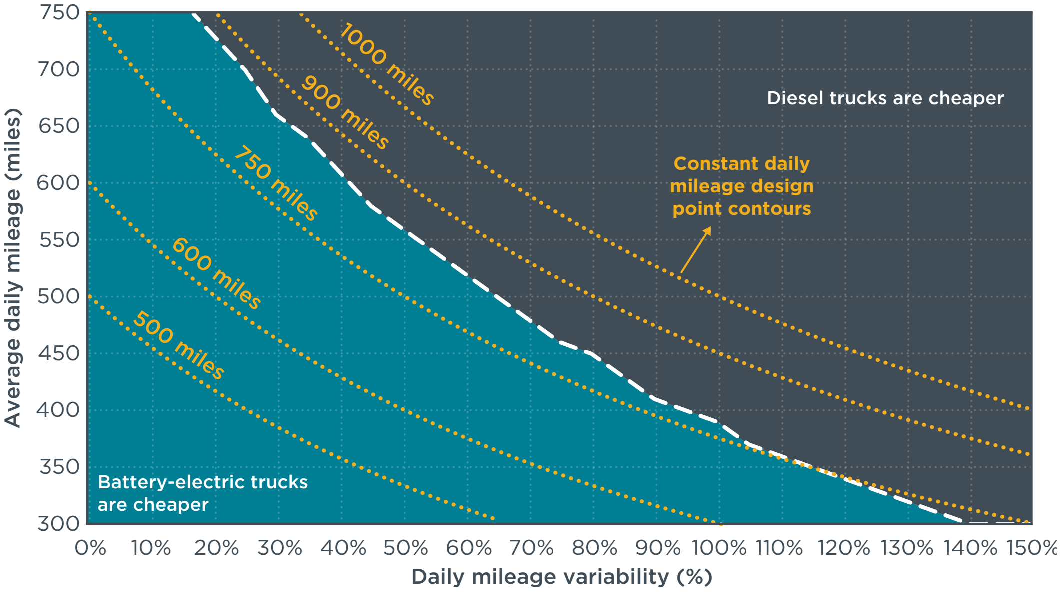


**Figure 20.** Impact of daily mileage and mileage variability on the TCO of MY 2040 battery electric and diesel trucks.

Generally, a higher average daily mileage or higher mileage variability will result in a higher battery design point in miles; thus, larger and more expensive batteries are needed, increasing the TCO of battery electric trucks. On the other hand, although an increase in the average daily mileage will require a larger battery size, the truck's annual mileage will also increase, benefiting battery electric trucks as their operational expenses per mile are much lower than their diesel counterparts.

This tradeoff is clearly presented in Figure 20. Battery electric trucks are expected to record a lower TCO than diesel trucks, even for average daily mileages reaching 750 miles, as long as the day-to-day mileage variability is low. As daily mileage variability increases, battery electric trucks will struggle to reach TCO parity with their diesel counterparts. For example, for an average daily mileage of 750 miles without any variability, the battery design point is 750 miles. In this case battery electric trucks record a lower TCO than diesel trucks. On the contrary, for a 300-mile average daily mileage coupled with a 150% variability, diesel trucks are expected to record a lower TCO than battery electric trucks, although the battery design point in this case is also 750 miles. This is driven by the fact that the annual truck mileage is much higher in the first case, counterweighting the higher cost of larger batteries due to the lower operational costs of battery electric trucks.

In conclusion, battery electric trucks can achieve better TCO than their diesel counterparts even for very high daily mileages, given that their day-to-day mileage variability is low.

# CONCLUSIONS

This study evaluates the economic viability of several powertrain technologies for Class 8 long-haul trucks in the United States between 2022 and 2040. In addition to conventional diesel trucks, we quantify the total cost of ownership of several alternative technologies, including battery electric, hydrogen fuel-cell, and hydrogen internal combustion engine trucks.

We arrive at the following main findings:

» **Battery electric long-haul trucks are expected to reach total cost of ownership parity with diesel trucks in all representative states considered in this analysis before 2030**. Given their higher energy efficiency and lower operational expenses, battery electric trucks are expected to become cheaper than their diesel counterparts in all selected states by the end of the decade.

» **Hydrogen fuel-cell and hydrogen internal combustion engine trucks operating in long-haul will struggle to become cost competitive compared to their diesel counterparts**. Hydrogen fuel-cell and hydrogen ICE trucks are expected to be roughly 25% and 50% more expensive, respectively, to own and operate than diesel trucks by 2030. The high hydrogen fuel costs are the main factor behind this behavior. Green hydrogen fuel prices in the United States are estimated to range between $9.00/kg and $11.00/kg by 2030, including the tax subsidies in the Inflation Reduction Act. For hydrogen fuel-cell trucks to become cost-competitive with diesel trucks during the next decade, green hydrogen prices need to range between $5.00/kg and $7.00/kg.

» **Battery electric trucks are expected to be the most cost-effective zero-emission truck technology for long-haul applications, recording a significantly lower total cost of ownership than hydrogen fuel-cell trucks**. Battery electric trucks benefit from a considerably higher fuel economy than their hydrogen fuel-cell counterparts, which results in much lower operational expenses. This yields a lower TCO for the battery electric technology. Given our modeled charging costs in several states of between $0.15/kWh and $0.30/kWh, green hydrogen fuel prices would have to be as low as $3.00/kg to $6.50/kg for hydrogen fuel-cell trucks to reach TCO parity with diesel trucks during the next decade, a range that is most likely to fall out of the expected green hydrogen fuel price range by 2030.

» **Hydrogen fuel-cell trucks will be the cheaper hydrogen-powered technology for long-haul applications, driven by their better fuel economy compared to hydrogen internal combustion engine trucks**. Hydrogen ICE trucks may have a better TCO than hydrogen fuel-cell trucks in the short term if hydrogen fuel prices are low enough due to the high MSRP of hydrogen fuel-cell trucks during the early market. However, as fuel-cell technology costs decrease in the long term, hydrogen fuel-cell trucks are expected to have a better TCO even for very low hydrogen fuel prices.

» **At the national level, battery electric trucks are expected to record the lowest total cost of ownership among all truck technologies for more than two-thirds of long-haul trucking activity by 2030**. Given the variations in diesel, hydrogen, and charging costs among states and the uncertainty in technology costs evolution between 2022 and 2040, battery electric trucks are the most cost-effective technology for almost 67% of the cases. This number will increase to 84% by 2040, driven by the expected reduction in battery prices and the rollout of MW charging infrastructure.

- **For very high daily mileages, battery electric trucks can still achieve a better total cost of ownership than their diesel counterpart.** As the truck's average daily mileage or mileage variability increases, larger batteries are needed to meet the truck's energy needs on the most demanding days, which increases the MSRP of battery electric trucks. However, given that the operations cost per mile of battery electric trucks is lower than that of diesel trucks, higher average daily mileages benefit the TCO of battery electric trucks relative to diesel. Overall, battery electric trucks are expected to record a better TCO for average mileages as high as 750 miles per day, provided that the day-to-day variability is low.

Based on the analysis presented in this study, battery electric trucks have the potential to ensure a cost-effective transition from the current diesel truck fleets in the United States before the end of the decade, providing a significant reduction GHG emissions from in the heavy-duty vehicle sector. Even for semi-trucks operating in long-haul, which are considered among the most challenging truck classes to decarbonize, the TCO of battery electric trucks is likely to become lower than that of diesel trucks as early as 2027 in some states and by 2030 for all considered states in this analysis.

Given the urgency of the climate crisis and the need for rapid and deep decarbonization of the heavy-duty vehicle sector GHG emissions, our study sheds light on the role that zero-emission technologies can play in the Phase 3 HDV GHG emissions standards. Our findings show that there is an opportunity for significant electrification by 2030 and beyond to support more stringent standards.

# REFERENCES

Basma, H., Beys, Y., & Rodríguez, F. (2021). *Battery electric tractor-trailers in the European Union: A vehicle technology analysis*. International Council on Clean Transportation. https://theicct.org/publication/battery-electric-tractor-trailers-in-the-european-union-a-vehicle-technology-analysis/

Basma, H., & Rodríguez, F. (2022). *Fuel Cell Electric Tractor-Trailers: Technology Overview and Fuel Efficiency*. International Council on Clean Transportation. https://theicct.org/publication/fuel-cell-tractor-trailer-tech-fuel-jul22/

Basma, H., Rodríguez, F., Hildermeier, J., & Jahn, A. (2022). *Electrifying last-mile delivery: A total cost of ownership comparison of battery-electric and diesel trucks in Europe*. International Council on Clean Transportation. https://theicct.org/publication/tco-battery-diesel-delivery-trucks-jun2022/

Basma, H., Saboori, A., & Rodríguez, F. (2021). *Total cost of ownership for tractor-trailers in Europe: Battery electric versus diesel*. International Council on Clean Transportation. https://theicct.org/publication/total-cost-of-ownership-for-tractor-trailers-in-europe-battery-electric-versus-diesel/

Basma, H., Zhou, Y., & Rodríguez, F. (2022). *Fuel-cell hydrogen long-haul trucks in Europe: A total cost of ownership analysis*. International Council on Clean Transportation. https://theicct.org/publication/eu-hvs-fuels-evs-fuel-cell-hdvs-europe-sep22/

Bennett, J., Mishra, P., Miller, E., Borlaug, B., Meintz, A., & Birky, A. (2022). *Estimating the Breakeven Cost of Delivered Electricity to Charge Class 8 Electric Tractors*. National Renewable Energy Laboratory. https://doi.org/10.2172/1894645

Burke, A., & Zhao, J. (2017). *Cycle Life of Lithium-ion Batteries in Combination with Supercapacitors: The effect of load-leveling*. Presented at the EVS30 Symposium, Stuttgart, Germany. https://steps.ucdavis.edu/wp-content/uploads/2017/05/BURKE-ZHAO-EVS30Lifecyclepaper2017_ver1.pdf

Burnham, A., Gohlke, D., Rush, L., Stephens, T., Zhou, Y., Delucchi, M. A., Birky, A., Hunter, C., Lin, Z., Ou, S., Xie, F., Proctor, C., Wiryadinata, S., Liu, N., & Boloor, M. (2021). *Comprehensive Total Cost of Ownership Quantification for Vehicles with Different Size Classes and Powertrains* [ANL/ESD-21/4]. Argonne National Laboratory. https://doi.org/10.2172/1780970

Buysse, C. (2022). *Zero-emission bus and truck market in the United States and Canada: A 2021 update*. International Council on Clean Transportation. https://theicct.org/publication/update-ze-truck-bus-market-us-can-sept22/

Buysse, C., & Sharpe, B. (2020). *California's Advanced Clean Trucks regulation: Sales requirements for zero-emission heavy-duty trucks*. International Council on Clean Transportation. https://theicct.org/publication/californias-advanced-clean-trucks-regulation-sales-requirements-for-zero-emission-heavy-duty-trucks/

Buysse, C., Sharpe, B., & Delgado, O. (2021). *Efficiency technology potential for heavy-duty diesel vehicles in the United States through 2035*. International Council on Clean Transportation. https://theicct.org/publication/efficiency-technology-potential-for-heavy-duty-diesel-vehicles-in-the-united-states-through-2035/

Daimler Truck AG. (2023). *Environment | Daimler Truck*. https://www.daimlertruck.com/en/nachhaltigkeit/e-environment

Federal Highway Administration. (2018). *2018 HPMS Public Release* [dataset]. https://www.fhwa.dot.gov/policyinformation/hpms/shapefiles.cfm

Florida Power and Light. (2023). *Buisness rates and clauses*. https://www.fpl.com/content/dam/fplgp/us/en/northwest/pdf/rates/electric-tariff-section8.pdf

Georgia Power. (2022). *Electric service tariff*. https://www.georgiapower.com/content/dam/georgia-power/pdfs/electric-service-tariff-pdfs/PLL-13.pdf

Hunter, C., Penev, M., Reznicek, E., Lustbader, J., Birky, A., & Zhang, C. (2021). *Spatial and Temporal Analysis of the Total Cost of Ownership for Class 8 Tractors and Class 4 Parcel Delivery Trucks* (NREL/TP-5400-71796). National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/71796.pdf

Inflation Reduction Act. Pub. L No: 117-169. (2022). https://www.congress.gov/117/plaws/publ169/PLAW-117publ169.pdf

International Council on Clean Transportation. (2022). *ICCT comments on the proposed Advanced Clean Fleets regulation*. https://theicct.org/pc-acf-reg-oct22/

Loszka, M., Martin, R., Guyon, O., & Leduc, P. (2022). *Transports lourds fonctionnant à l'hydrogène*. IFP Energies nouvelles [Heavy transport powered by hydrogen: Energy, economic and environmental analysis]. https://librairie.ademe.fr/mobilite-et-transport/5722--tranplhyn-transports-lourds-fonctionnant-a-l-hydrogene.html

Mao, S., Basma, H., Ragon, P.-L., Zhou, Y., & Rodríguez, F. (2021). *Total cost of ownership for heavy trucks in China: Battery electric, fuel cell, and diesel trucks*. International Council on Clean Transportation. https://theicct.org/publication/total-cost-of-ownership-for-heavy-trucks-in-china-battery-electric-fuel-cell-and-diesel-trucks/

McDaniel, J. (2022, August 16). *Navistar launches new truck with its 'last' internal combustion engine*. Bulk Transporter. https://www.bulktransporter.com/equipment/trucks/article/21248846/navistar-launches-new-truck-last-ice-powertrain

National Grid. (2022). *Service Rates*. https://www.nationalgridus.com/Upstate-NY-Business/Rates/Service-Rates

National Renewable Energy Laboratory. (2023). *Fleet DNA: Commercial Fleet Vehicle Operating Data*. https://www.nrel.gov/transportation/fleettest-fleet-dna.html

Nykvist, B., & Olsson, O. (2021). The feasibility of heavy battery electric trucks. *Joule*, 5(4) 737-1010. https://doi.org/10.1016/j.joule.2021.03.007

Office of the Federal Register. (2012, April 1). *26 CFR 145.4051-1—Imposition of tax on heavy trucks and trailers sold at retail.* [Government]. https://www.govinfo.gov/app/details/CFR-2012-title26-vol17/https%3A%2F%2Fwww.govinfo.gov%2Fapp%2Fdetails%2FCFR-2012-title26-vol17%2FCFR-2012-title26-vol17-sec145-4051-1

Oncore. (2022). *Tariffs for retail delivery service*. https://www.oncor.com/content/dam/oncorwww/documents/about-us/regulatory/tariff-and-rate-schedules/Tariff%20for%20Retail%20Delivery%20Service.pdf.coredownload.pdf

Pacific Gas and Electric Company. (2022). *Electricity schedule BEV – Buisness electric vehicle*. https://www.pge.com/tariffs/assets/pdf/tariffbook/ELEC_SCHEDS_BEV.pdf

Phadke, A., Khandekar, A., Abhyankar, N., Wooley, D., & Rajagopal, D. (2021). *Why Regional and Long-Haul Trucks are Primed for Electrification Now*. Lawrence Berkeley National Laboratory. https://eta-publications.lbl.gov/publications/why-regional-and-long-haul-trucks-are

Pohl, H., & Ridell, B. (2019). *Hydrogen storage in vehicles*. https://energiforsk.se/media/26373/6-hydrogen-storage-in-vehicles-hans-pohl-bengt-ridell.pdf

Puget Sound Energy. (2022). *Large demand general service*. https://www.pse.com/-/media/Project/PSE/Portal/Rate-documents/Electric/elec_sch_031.pdf

Ricardo Strategic Consulting. (2022). *E-truck Virtual Teardown: Final Report*. https://theicct.org/wp-content/uploads/2022/01/Final-Report-eTruck-Virtual-Teardown-Public-Version.pdf

Sharpe, B., & Basma, H. (2022). *A meta-study of purchase costs for zero-emission trucks*. International Council on Clean Transportation. https://theicct.org/publication/purchase-cost-ze-trucks-feb22/

Simcenter Amesim. (2022). *Simcenter Amesim | Siemens Software*. https://www.plm.automation.siemens.com/global/en/products/simcenter/simcenter-amesim.html

Slowik, P., Searle, S., Basma, H., Miller, J., Zhou, Y., Rodríguez, F., Buysse, C., Minjares, R., Kelly, S., Pierce, L., Orvis, R., & Baldwin, S. (2023). *Analyzing the impact of the Inflation Reduction Act on electric vehicle uptake in the United States*. International Council on Clean Transportation. https://theicct.org/publication/ira-impact-evs-us-jan23/

U.S. Energy Information Administration. (2022a). *Electricity data browser—Average retail price of electricity*. https://www.eia.gov/electricity/data/browser/#/topic/7?agg=0,1&geo=0000g&endsec=6&linechart=ELEC.PRICE.IL-COM.M&columnchart=ELEC.PRICE.IL-COM.M&map=ELEC.PRICE.IL-COM.M&freq=M&start=200101&end=202208&ctype=map&ltype=pin&rtype=s&maptype=0&rse=0&pin=

U.S. Energy Information Administration. (2022b). *Gasoline and Diesel Fuel Update—U.S. Energy Information Administration (EIA)*. https://www.eia.gov/petroleum/gasdiesel/

U.S. Environmental Protection Agency. (2022a). *Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2020*. https://www.epa.gov/system/files/documents/2022-04/us-ghg-inventory-2022-main-text.pdf

U.S. Environmental Protection Agency. (2022b). *MOVES3: Latest Version of Motor Vehicle Emission Simulator*. https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves

U.S. Environmental Protection Agency & U.S. Department of Transportation. (2016). *Greenhouse Gas Emissions and Fuel Efficiency Standards for Medium- and Heavy-Duty Engines and Vehicles–Phase 2* [Federal Register / Vol. 81, No. 206]. https://www.gpo.gov/fdsys/pkg/FR-2016-10-25/pdf/2016-21203.pdf

Volvo Trucks. (2022, September 1). *New report—High pressure on the transport industry to shift to electric*. https://www.volvotrucks.com/en-en/news-stories/press-releases/2022/sep/New-report-high-pressure-on-the-transport-industry-to-shift-to-electric.html

Wang, G., Miller, M., & Fulton, L. (2022). *Estimating Maintenance and Repair Costs for Battery Electric and Fuel Cell Heavy Duty Trucks*. University of California, Davis. https://escholarship.org/content/qt36c08395/qt36c08395_noSplash_589098e470b036b3010eae00f3b7b618.pdf?t=r6zwjb

Xie, Y., Basma, H., & Rodrigues, F. (2023). *Purchase costs of zero-emission trucks in the United States to meet future Phase 3 GHG standards*. International Council on Clean Transportation. https://theicct.org/publication/cost-zero-emission-trucks-us-phase-3-mar23/

# APPENDIX

**Table A1.** Summary of battery sizing approach

| MY | Charging power (kW) | Charging efficiency (%) | Daily mileage (miles) | Driver's break (hours) | Energy efficiency (kWh/mi) | Required design point (miles) | Battery size (kWh) | Actual design point (miles) |
|---|---|---|---|---|---|---|---|---|
| **2022** | 350 | 95% | 500 | 1 | 2.86 | 384 | 1,000 | **297** |
| **2023** | 350 | 95% | 500 | 1 | 2.80 | 381 | 1,000 | **303** |
| **2024** | 350 | 95% | 500 | 1 | 2.75 | 378 | 1,000 | **310** |
| **2025** | 350 | 95% | 500 | 1 | 2.69 | 376 | 1,000 | **316** |
| **2026** | 350 | 95% | 500 | 1 | 2.63 | 373 | 1,000 | **323** |
| **2027** | 1,000 | 95% | 500 | 1 | 2.57 | 300 | 900 | **300** |
| **2028** | 1,000 | 95% | 500 | 1 | 2.51 | 300 | 880 | **300** |
| **2029** | 1,000 | 95% | 500 | 1 | 2.45 | 300 | 860 | **300** |
| **2030** | 1,000 | 95% | 500 | 1 | 2.39 | 300 | 840 | **300** |
| **2031** | 1,000 | 95% | 500 | 1 | 2.34 | 300 | 820 | **300** |
| **2032** | 1,000 | 95% | 500 | 1 | 2.29 | 300 | 800 | **300** |
| **2033** | 1,000 | 95% | 500 | 1 | 2.23 | 300 | 780 | **300** |
| **2034** | 1,000 | 95% | 500 | 1 | 2.18 | 300 | 760 | **300** |
| **2035** | 1,000 | 95% | 500 | 1 | 2.12 | 300 | 740 | **300** |
| **2036** | 1,000 | 95% | 500 | 1 | 2.12 | 300 | 740 | **300** |
| **2037** | 1,000 | 95% | 500 | 1 | 2.12 | 300 | 740 | **300** |
| **2038** | 1,000 | 95% | 500 | 1 | 2.12 | 300 | 740 | **300** |
| **2039** | 1,000 | 95% | 500 | 1 | 2.12 | 300 | 740 | **300** |
| **2040** | 1,000 | 95% | 500 | 1 | 2.12 | 300 | 740 | **300** |

*Notes:* Values in red text represent the case where the actual design point is lower than the required design point. Values in green represent that case where the actual design point is equal to the required design point.

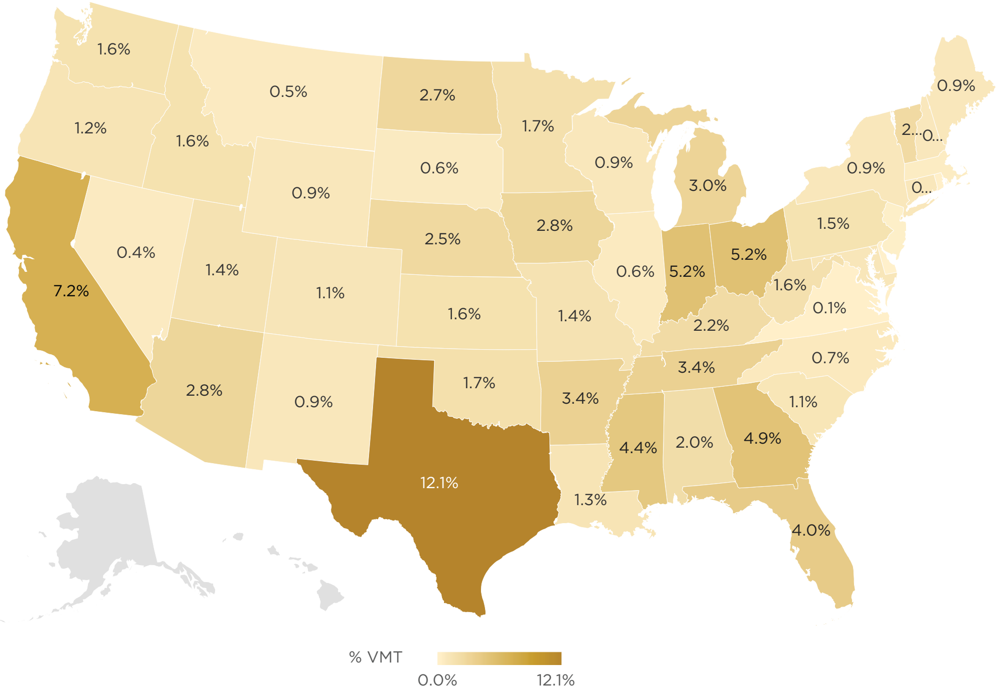


**Figure A1.** Percent distribution of tractor-trailers vehicles miles travelled in the United States Data adopted from Federal Highway Administration (2018).

## California

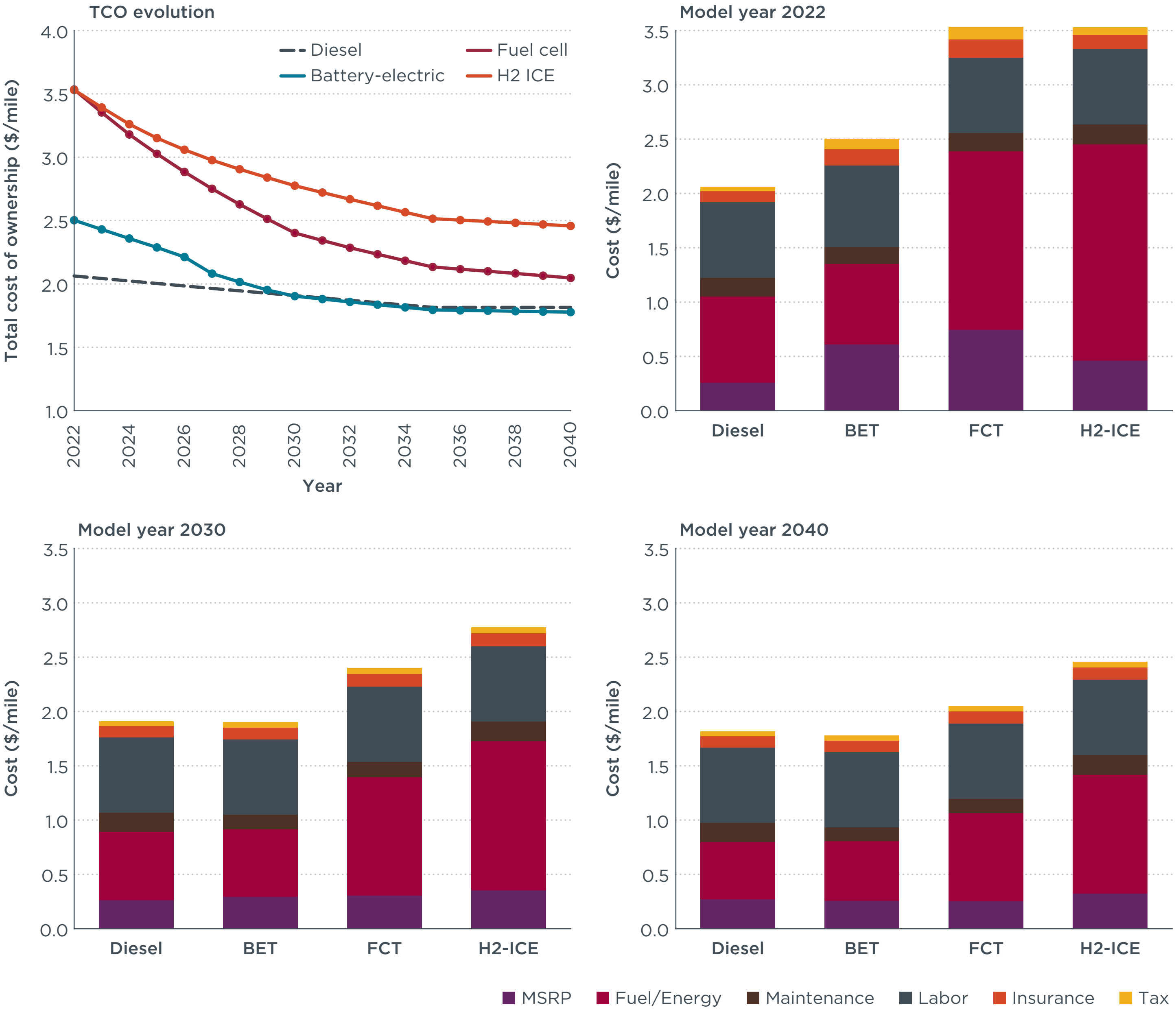


**Figure A2.** Total cost of ownership (TCO) evolution between 2022 and 2040 and TCO breakdown for truck MYs 2022, 2030, and 2040 in California.

## Florida

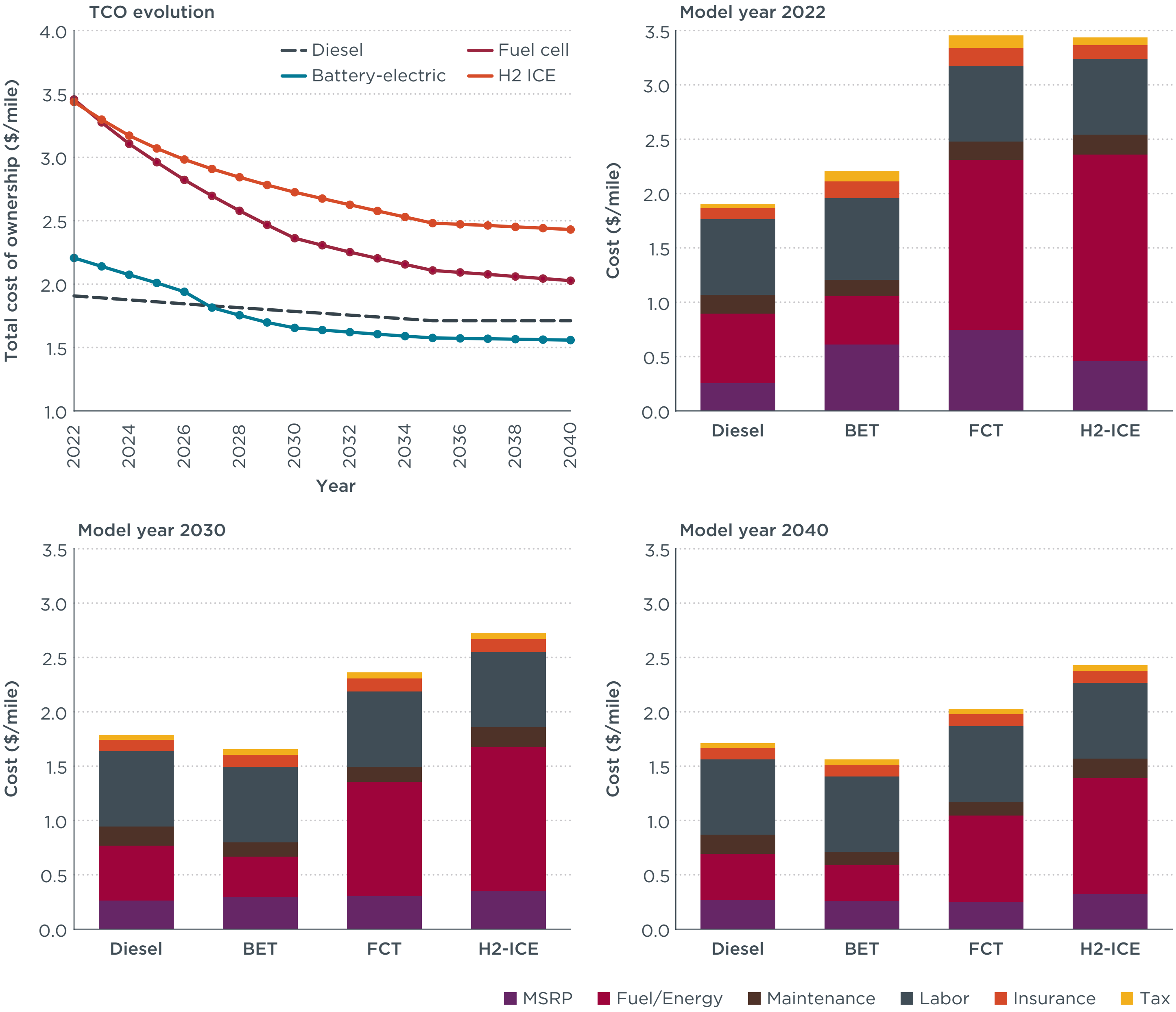


**Figure A3.** Total cost of ownership (TCO) evolution between 2022 and 2040 and TCO breakdown for truck MYs 2022, 2030, and 2040 in Florida.

## Georgia

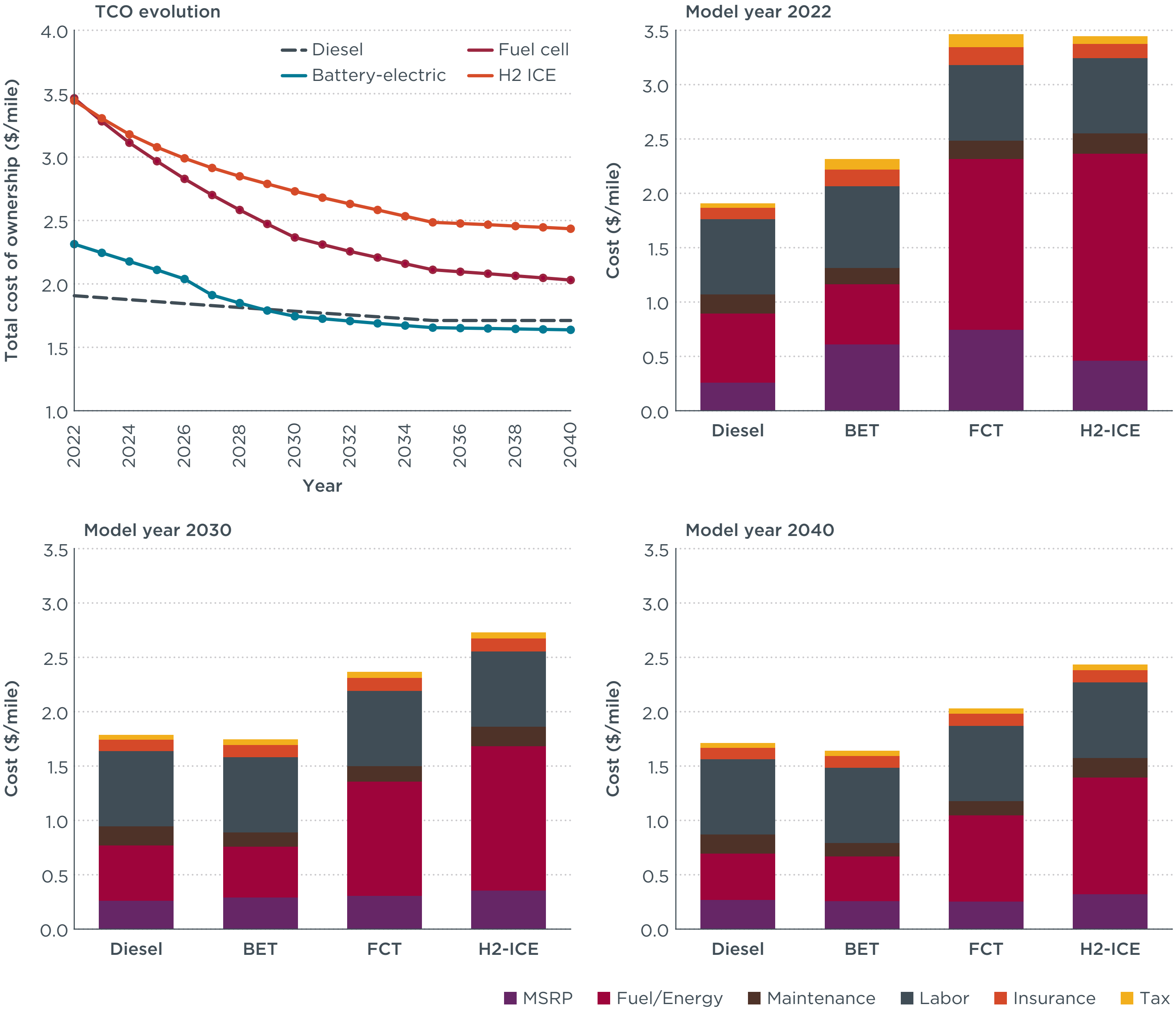


**Figure A4.** Total cost of ownership (TCO) evolution between 2022 and 2040 and TCO breakdown for truck MYs 2022, 2030, and 2040 in Georgia.

## Illinois

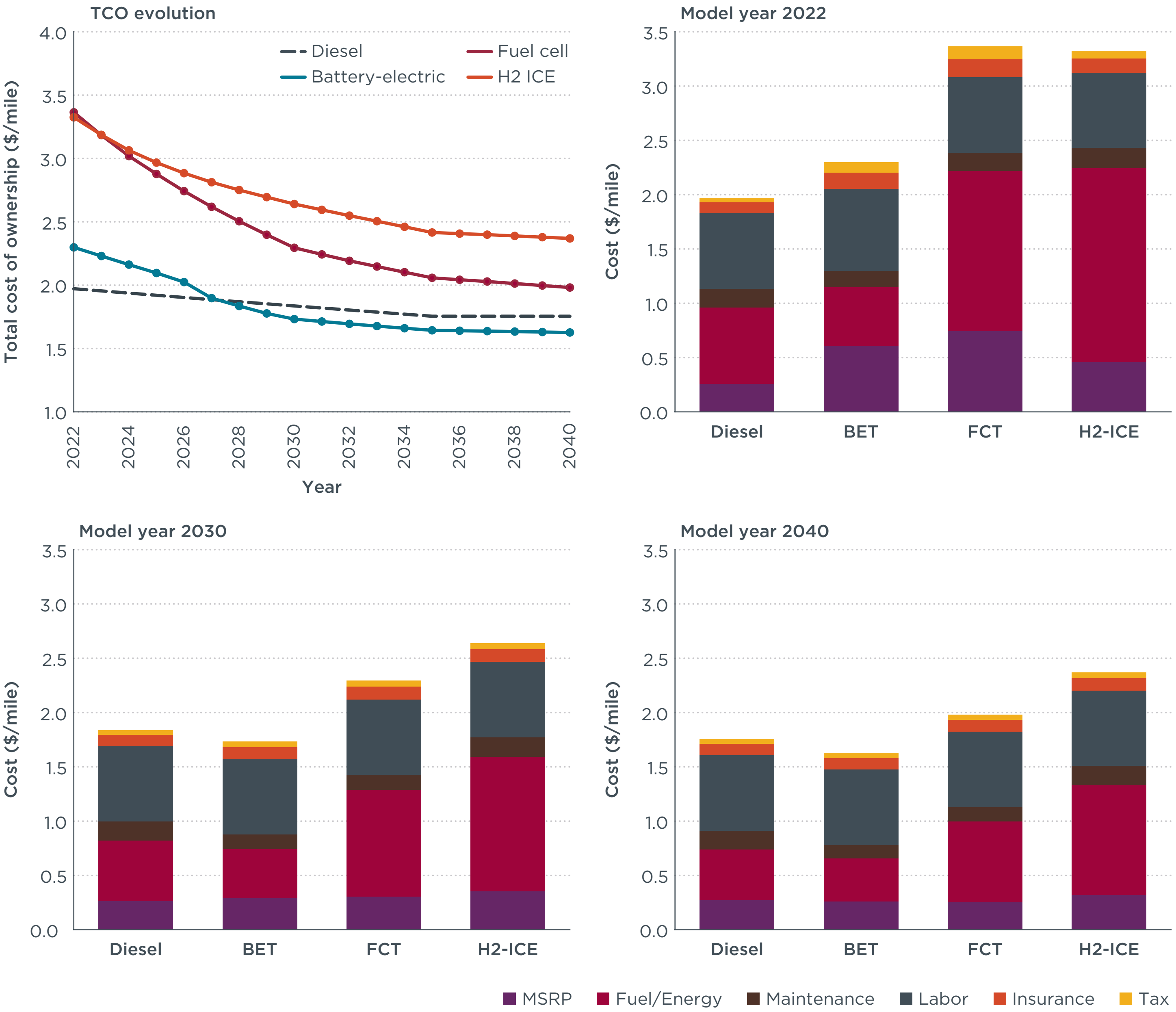


**Figure A5.** Total cost of ownership (TCO) evolution between 2022 and 2040 and TCO breakdown for truck MYs 2022, 2030, and 2040 in Illinois.

## Washington

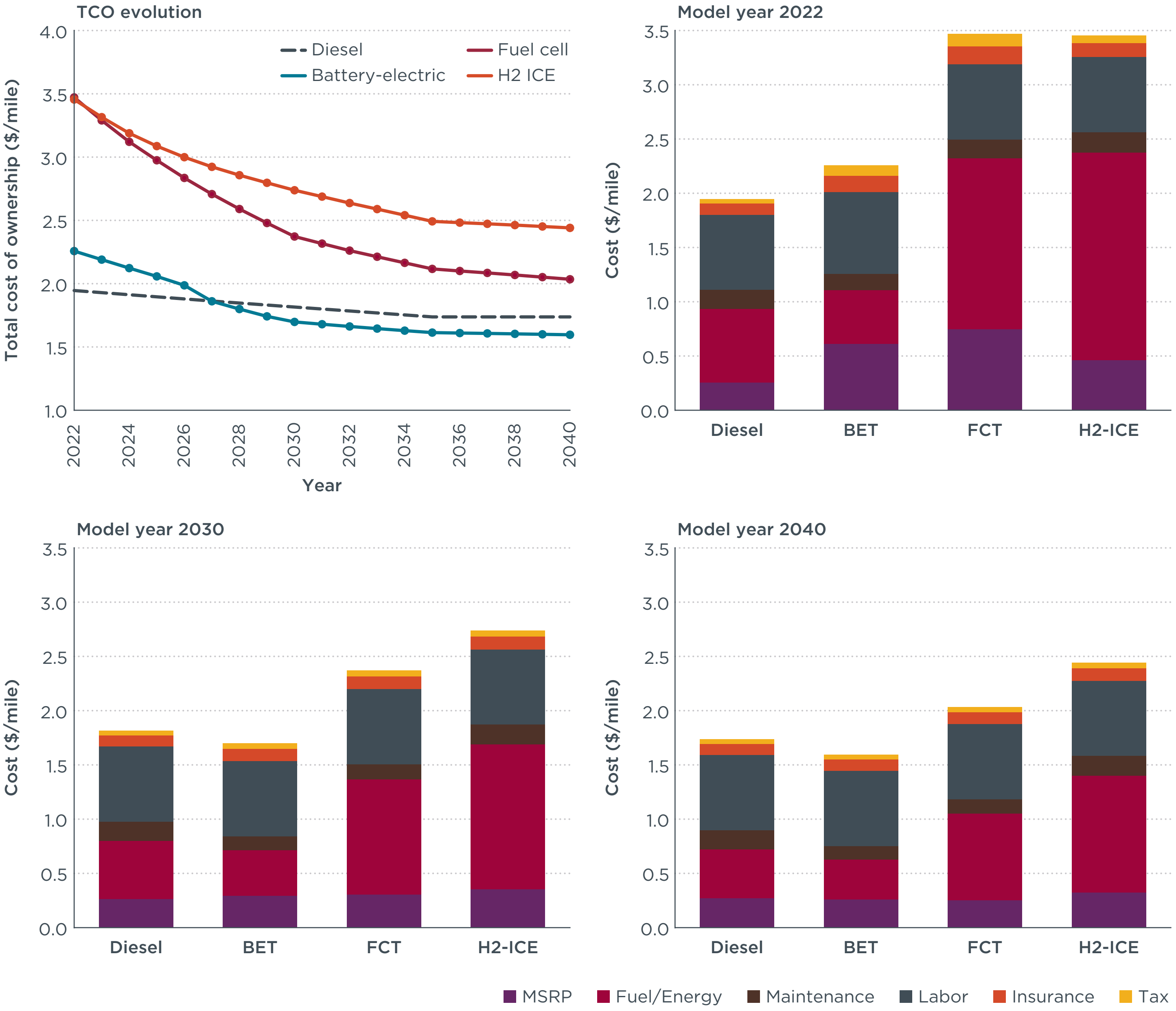


**Figure A6.** Total cost of ownership (TCO) evolution between 2022 and 2040 and TCO breakdown for truck MYs 2022, 2030, and 2040 in Washington.

## New York

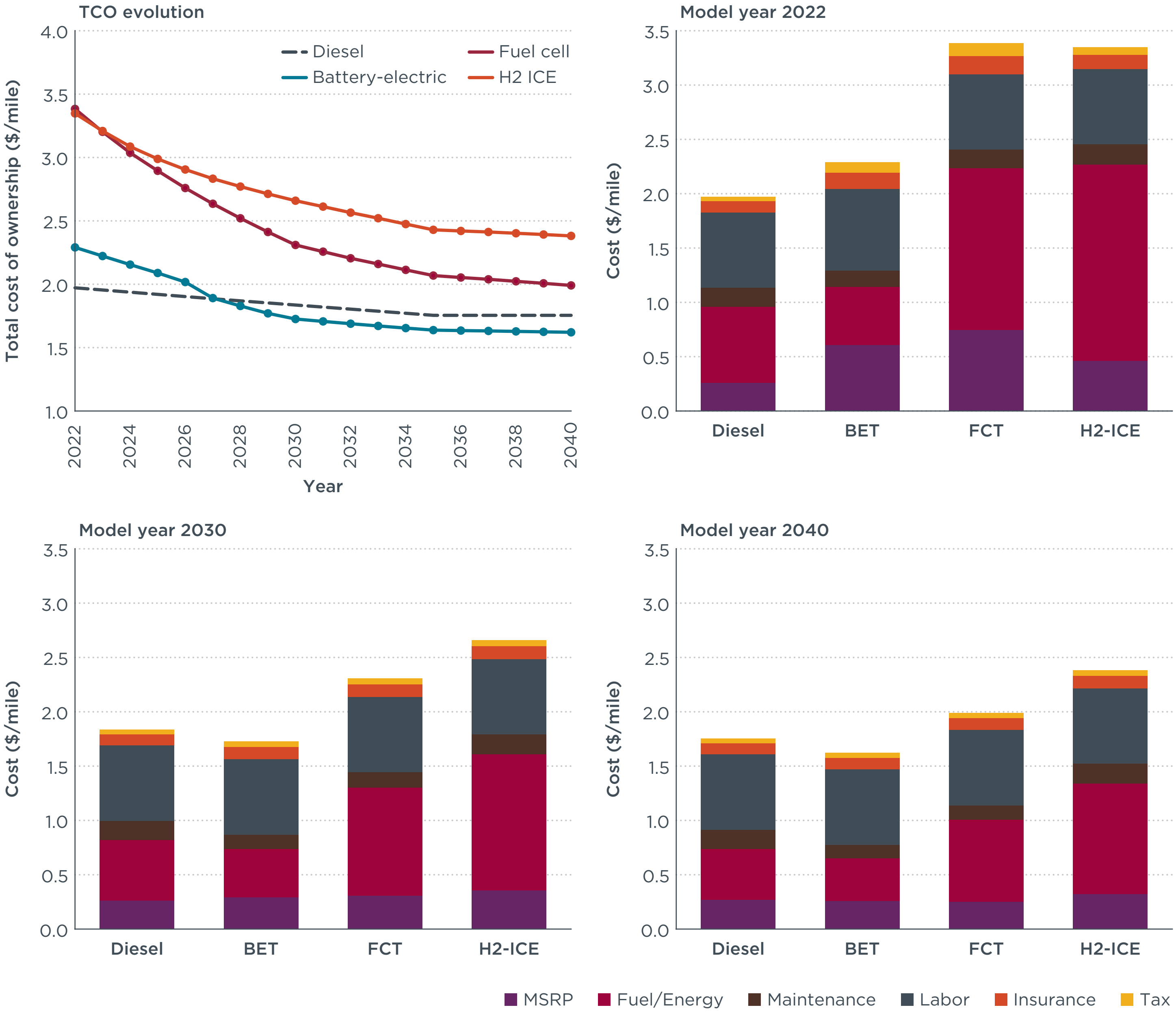


**Figure A7.** Total cost of ownership (TCO) evolution between 2022 and 2040 and TCO breakdown for truck MYs 2022, 2030, and 2040 in New York.

## Texas

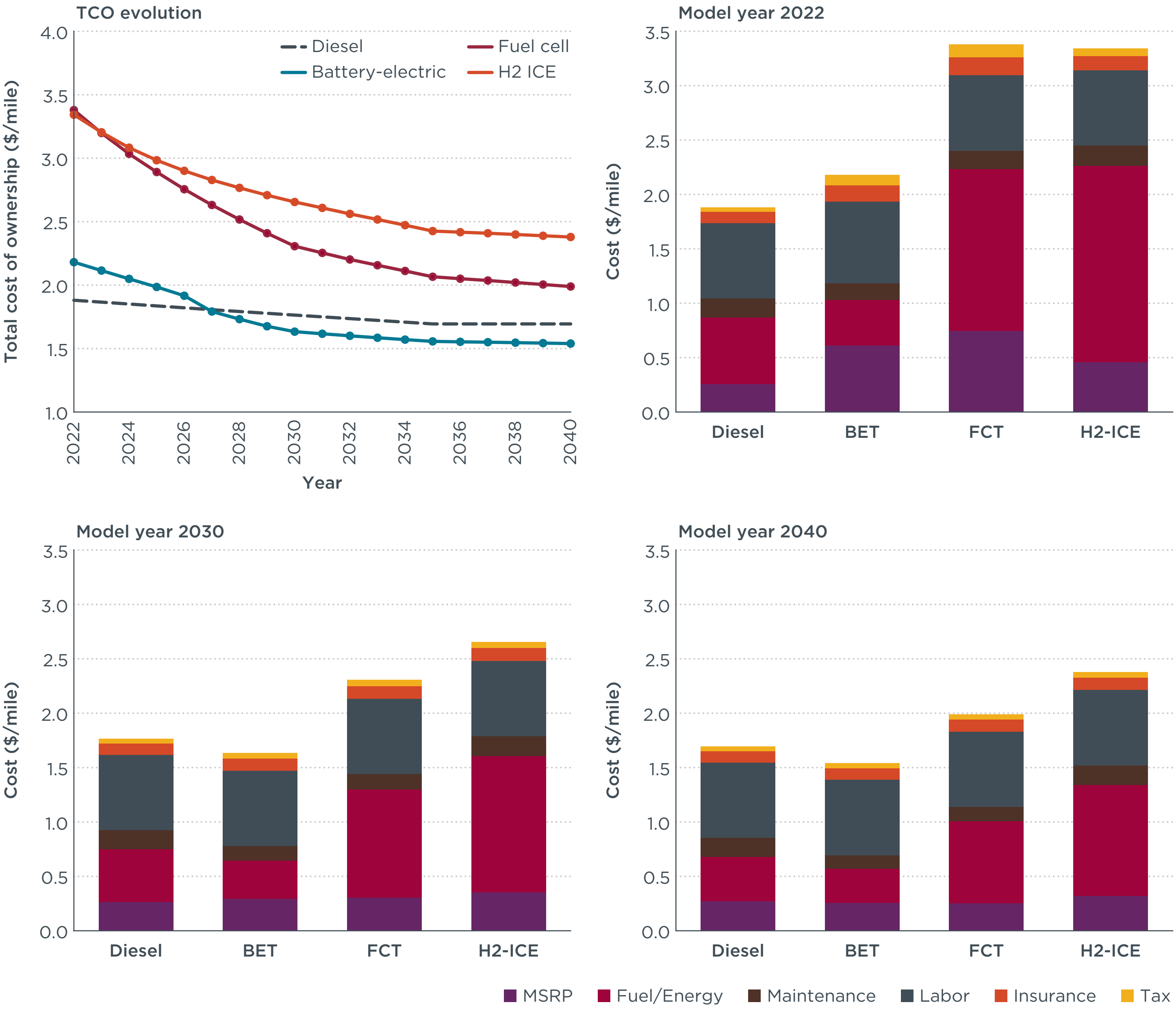


**Figure A8.** Total cost of ownership (TCO) evolution between 2022 and 2040 and TCO breakdown for truck MYs 2022, 2030, and 2040 in Texas.

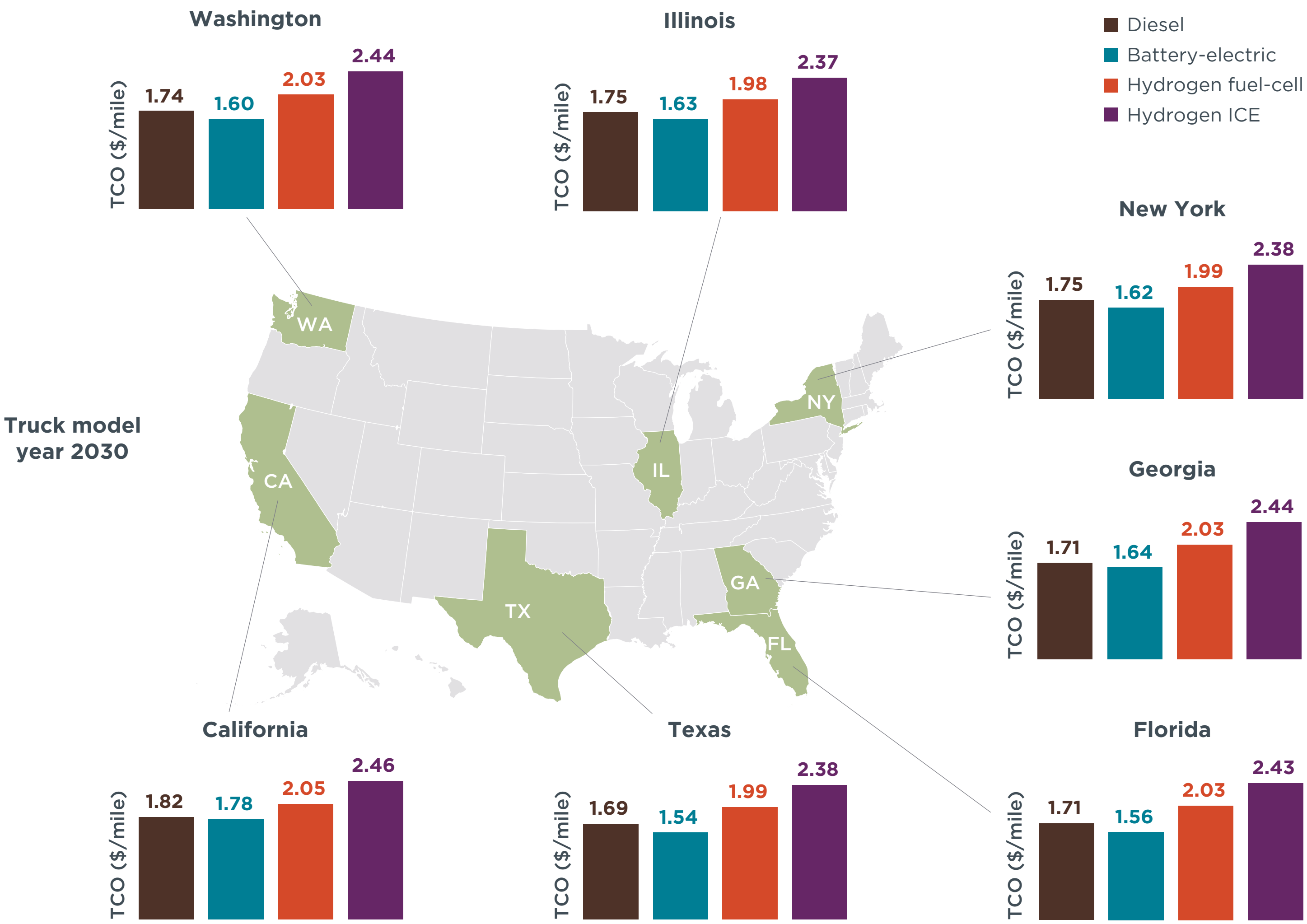


**Figure A9.** State-specific total cost of ownership for different MY 2040 truck technologies.