Title

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Market Prospects of Fuel Cell vs. Battery-Electric Trucks in Medium- and Heavy-Duty Segments in California, 2025 to 2040

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Abstract

This report evaluates the market prospects for medium- and heavy-duty fuel cell electric trucks (FCETs) and battery-electric trucks (BETs) in comparison to diesel trucks in California from 2025 to 2040. It specifically examines the market feasibility challenges facing FCETs and provides updates on technological advancements in fuel cell systems, including projections for future developments. The report presents a comprehensive cost analysis of BETs and FCETs, covering the vehicles and the necessary infrastructure. This includes total cost of ownership (TCO) considerations as well as non-cost factors such as driving range, refueling/recharging times, and their influence on the projected demand for these trucks. In additional, it provides a detailed assessment of infrastructure expenses, comparing the costs of battery-charging facilities for electric trucks with those of hydrogen refueling stations for FCETs. Finally, the study forecasts market shares under various scenarios over the next two decades, accounting for the impact of government incentives, infrastructure availability, and model diversity. The vehicle cost model indicates that fuel cell systems represent a significant portion of the initial cost for FCETs, expected to decrease from 40% to 30% for medium-duty trucks and from 20% for heavy-duty trucks by 2040. Although neither FCETs nor BETs are projected to reach initial cost parity with internal combustion engine vehicles by 2040, both are likely to achieve a lower total cost of ownership than diesel trucks due to savings on fuel and maintenance. FCETs are expected to be more competitive than BETs in heavy-duty applications due to faster refueling times, longer ranges, and lower upfront costs. Targeted incentives such as the federal Clean Vehicle Tax Credit and the Hybrid and California Zero-Emission Truck and Bus Voucher Incentive Project could help bridge the cost gap between FCETs and diesel trucks in the coming years, but the robust development of hydrogen infrastructure will be essential, particularly in the early stages. FCETs are positioned to lead the heavy-duty sector, and achieving the goals of the California Air Resources Board will require significant advancements in technology, infrastructure, and policy.

Keywords: zero emission vehicles; battery electric vehicle; fuel cell vehicle; market share; penetration; consumer preference; medium-duty vehicle; heavy-duty vehicle

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List of Acronyms

BET	battery-electric truck
CARB	California Air Resources Board
CVTC	Clean Vehicle Tax Credit
DOE	Department of Energy
FC	fuel cell
FCET	fuel cell electric truck
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
ICCT	International Council on Clean Transportation
ICEV	internal combustion engine vehicle
IRS	Internal Revenue Service
LH	liquid hydrogen
MD/HD	medium-duty/heavy-duty
PEM	proton exchange membrane
TCO	total cost of ownership
ZEV	zero-emission vehicle

Executive Summary

This report evaluates the market potential of medium- and heavy-duty fuel cell electric trucks (FCETs) in comparison to battery-electric trucks (BETs) in California from 2025 to 2040. It identifies key challenges for these technologies, reviews technological advancements, and projects future developments in fuel cell systems. While we provide a particularly detailed assessment of fuel cell trucks, we also include our latest estimates for battery-electric trucks. The analysis offers a comprehensive breakdown of technology and infrastructure costs, comparing the expenses associated with hydrogen refueling stations and battery-charging facilities. We used the purchase probability analysis-based dynamic discrete choice approach to forecast market shares for hydrogen FCETs and BETs under several scenarios, examining the effects of government incentives, infrastructure availability, and truck model diversity.

An overview of our results in terms of vehicle purchase costs, total cost of ownership (TCO), and potential market shares is presented in **Figure ES1** to **ES3**. While additional scenarios are explored in the body of the paper, these figures provide a general summary of the outlook. The results indicate that FCETs are unlikely to achieve initial cost parity with internal combustion engine vehicles by 2040 (see **Figure ES1**). However, their TCO is expected to converge with, and potentially undercut, that of diesel trucks by 2040. Additionally, by 2040, FCETs may offer a lower TCO than BETs, particularly for heavier trucks such as Class 7 and Class 8 (refer to **Figure ES2**). The convergence of costs suggests that government procurement incentives, including IRS tax credits and California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP; **Figure 9**), could play a pivotal role in closing the cost gap between FCETs, BETs, and conventional vehicles (**Figure 6**), assuming no further cost reductions through 2040. Specifically, these incentives can effectively bridge the gap between FCETs and ICETs across all truck segments, from Class 3 to Class 8, due to the substantial reduction in the upfront cost of FCETs. However, for Class 8 heavy-duty long-haul trucks, the incentives are insufficient to fully cover the cost gap between BETs and ICETs, as the high initial cost of BETs, due to their large battery systems, persists even in 2040.

As shown in **Figure ES3**, significant progress in scaling up ZEV market shares in the heavy-duty truck sector may be limited until 2030 without strong policy support. However, by 2040, the sector shows potential to achieve a 100% ZEV market share for Class 7 short-haul trucks and approximately 80% for Class 8 long-haul trucks. This scenario assumes strong growth in vehicle and fuel production, the availability of clean, low-cost hydrogen, substantial procurement incentives to offset most of the cost differential with ICE vehicles, and a sufficient variety of truck models to meet specific market demands, including those for low-cost, long-range, and high-utilization sectors.

In conclusion, the report emphasizes that infrastructure, vehicle purchase incentives, and technological advancements are crucial for the successful market penetration of FCETs. While BETs currently lead in technological maturity, FCETs, particularly in the heavy-duty vehicle segment, have strong potential to capture significant market share due to their operational advantages, including longer range, faster refueling, and greater durability in long-distance applications.

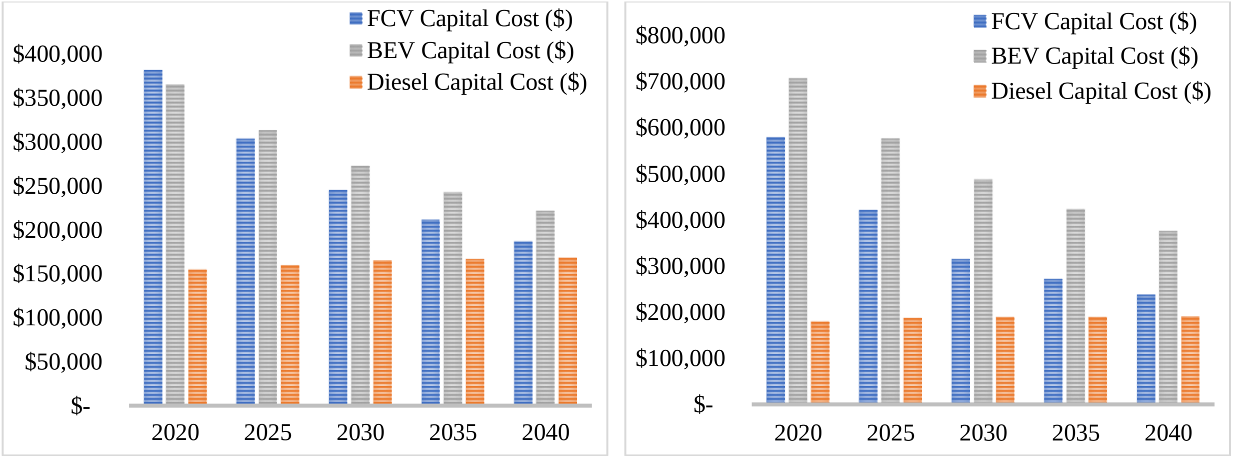


Figure ES1. Vehicle costs for battery electric and fuel cell Class 7 short-haul (left) and Class 8 long-haul (right) trucks.

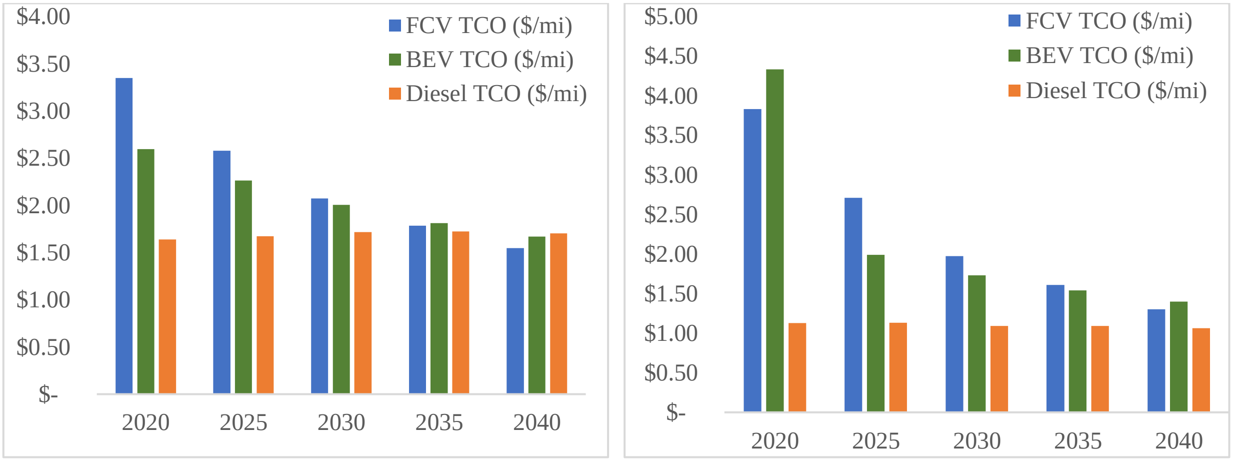


Figure ES2. TCOs for battery electric and fuel cell Class 7 short-haul (left) and Class 8 long-haul (right) trucks.

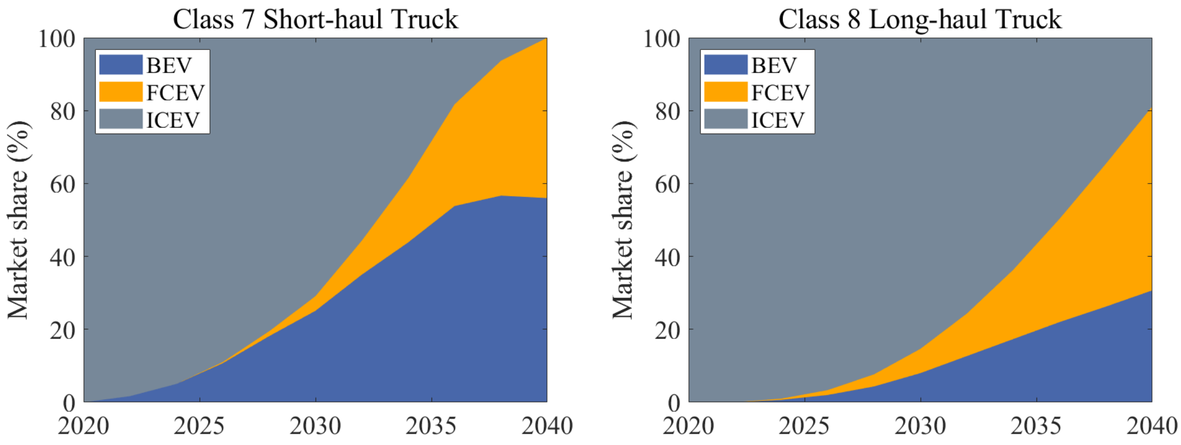


Figure ES3. Market penetration of heavy-duty vehicles (procurements support, enhanced infrastructure and improved model availability).

1 Introduction

The transition to zero-emission vehicles (ZEVs) is a critical component of global efforts to reduce greenhouse gas emissions and combat climate change. This report delves into the near-term (up to 2030) and far-term (up to 2040 and beyond) market prospects of battery-electric and fuel cell medium-duty/heavy-duty trucks (MD/HDTs). Unlike light-duty ZEVs, MD/HDTs are predominantly used in commercial applications and play key roles in meeting CO_2 mitigation targets [1]. Consequently, the key decision factors for purchasing ZETs in this category are notably distinct. Critical decision factors for commercial ZETs include vehicle purchase price, range, refueling time, battery and FC lifetime, and operating costs. These factors are crucial for LD ZEVs as well [2]-[4], but they have an amplified impact on the daily operational efficiency and economic viability of MD/HD ZETs.

Technological advancements play a pivotal role in the viability and adoption of MD/HD ZETs. Battery-electric trucks (BETs) currently rely on high-capacity lithium-ion batteries. Innovations in battery technology and cost reduction have greatly improved vehicle performance over the past decade [5]. However, challenges such as battery aging [6]-[8], safety issues [9],[10], and relatively slow charging times impede their mass adoption, especially for heavy trucks. On the other hand, fuel cell technology offers a distinct set of advantages and challenges. Fuel cell electric trucks (FCETs) use hydrogen as a fuel source, which is converted into electricity through a chemical reaction within the fuel cell stack [11]. Recent developments in fuel cell efficiency, durability, and cost reduction have made FCETs a competitive alternative to BETs [12]. Innovations in hydrogen production, particularly green hydrogen from renewable sources, and advancements in hydrogen storage and refueling infrastructure are critical for the widespread adoption of FCETs.

The core focus of this report is the market feasibility of FCETs in competition with BETs across various classes. Section 2 provides a comprehensive review of the current (2023) markets for ZEVs in key regions: China, Korea, Europe, the United States, and California, establishing a benchmark for future market developments. In Section 3, we identify and discuss the key market feasibility issues in detail. Sections 4 and 5 present updates on FC system performance and cost, as well as FCET performance and cost. Section 6 examines the infrastructure technologies for ZEVs, comparing the costs associated with battery charging and hydrogen refueling for fleets. In Section 7, we project the market shares of battery-electric and hydrogen FCETs under varying market conditions in the near and far terms. Finally, Section 8 reviews the prospective markets for FCETs of various classes, and Section 9 summarizes the study's conclusions. This report aims to provide a thorough understanding of the competitive landscape for MD/HD ZETs, highlighting the critical factors that will shape the market for FCETs and BETs in the coming decades. The technological advances discussed here are essential for stakeholders to navigate the evolving landscape and make informed decisions in the transition to zero-emission transportation.

2 Status of FC MH/HD trucks markets worldwide

The status of ZEV markets, particularly for MH/HDV, varies significantly across China, Europe, and the United States, including California, reflecting differences in policy, infrastructure development, and market readiness. As of early 2024, these regions have shown distinct patterns of adoption and progress in integrating ZEVs into their transportation ecosystems.

2.1 China

China is leading in the electrification of MH/HDVs, driven by strong government mandates, substantial investments in charging infrastructure, and incentives for manufacturers and buyers. The country has the world's largest electric bus fleet, and its policies have been aggressively pushing for cleaner commercial vehicles to combat pollution. The government mandate requires automakers to earn credits through the production of ZEVs, including heavy-duty trucks and buses, which has spurred significant growth in this sector. Local manufacturers such as BYD and national policies targeting urban air quality improvements are pivotal in this acceleration. China's strides in the ZEV market are reflective of its comprehensive commitment to a sustainable transportation future. This is evidenced by the government's overarching hydrogen strategy and the concrete steps being taken to meet the ambitious goal of carbon neutrality by 2060. The country's significant investments in hydrogen production—currently the largest in the world—are gradually shifting toward greener methods such as water electrolysis. This shift is a strategic move to reduce the carbon footprint of hydrogen production, which is presently predominantly sourced from coal and natural gas (NG).

In terms of market dynamics, China is focusing not only on infrastructure but also on vehicle adoption rates. The Chinese government's promotion of hydrogen as a cornerstone of its energy policy is exemplified by the targets set by the National Development and Reform Commission. The commission aims to have 50,000 hydrogen-fueled vehicles by 2025 [13], alongside a doubling of hydrogen refueling stations, demonstrating the country's commitment to establishing a robust hydrogen economy. Projections for FCET adoption indicate a significant displacement of diesel-fueled trucks, with thousands of fuel cell electric trucks expected to be operational in the next few years. The capital city of Beijing is at the forefront, with expectations to introduce 10,000 fuel cell vehicles [14], emphasizing the local government's role in achieving national objectives. The market's expansion is driven by domestic initiatives and international partnerships. The recent order for 1,100 fuel cell electric trucks highlights the demand for clean energy vehicles and confidence in hydrogen technology's readiness and reliability [15]. Overall, China's market for hydrogen fuel cells is on a robust upward trajectory, signaling the country's proactive approach to decarbonizing its transportation sector. The confluence of government support, international collaborations, and a forward-looking industrial base indicates a future where ZEVs play a vital role in China's—and potentially the world's—transport ecosystem.

2.2 Korea

South Korea’s government has set ambitious goals for integrating hydrogen-powered buses and trucks into the commercial mobility sector. The government aspires to have 20,000 buses and 10,000 trucks fueled by hydrogen by 2030. However, the current market phase for hydrogen commercial vehicles in South Korea mirrors that of Japan [16]. While there has been a significant increase in the annual shipments of FC buses since the introduction of the first model in 2018, the market remains small, with fewer than 200 hydrogen buses in operation as of mid-2022. This situation highlights a considerable gap from the set targets, a disparity even greater than that in Japan. Furthermore, the debut of hydrogen FCETs in 2021 marked a critical step in expanding this technology's footprint, with the initial batch of five trucks being deployed in Incheon and Ulsan as part of a pilot project. This initiative, led by the Korean government and Hyundai Motor, benefited from over 50% of direct purchase subsidies from the Korean Ministry of Environment. Despite these efforts, the path to achieving the goal of deploying 10,000 hydrogen trucks by 2030 is difficult.

Notably, South Korean-manufactured hydrogen heavy-duty trucks have commenced serious production for markets abroad, with launches in Switzerland and upcoming availability in Germany, New Zealand, and the United States (California). This indicates readiness for larger-scale deployment within South Korea itself. However, the development of hydrogen refueling infrastructure remains a critical bottleneck. The pace of hydrogen station construction will play a pivotal role in determining whether South Korea can meet its strategic targets for hydrogen vehicles in the upcoming decade.

2.3 Europe

Europe exhibits a strong commitment to reducing carbon emissions from the transportation sector, with several countries implementing policies to encourage the adoption of ZEVs, including for MD/HDVs. The European Green Deal and the Fit for 55 package are driving efforts towards a 55% reduction in greenhouse gases by 2030, compared to 1990 levels [17]. This has led to an increase in electric buses, delivery trucks, and other commercial vehicles across the continent. Countries such as Norway, the Netherlands, and Germany are leading in adoption rates, supported by extensive charging infrastructure and incentives. The EU's CO_2 standards for HDVs are also pushing manufacturers towards electrification. The European market for ZEVs, particularly trucks, is exhibiting a promising trend bolstered by supportive government policies and a shifting focus toward renewable energy and sustainable transportation. FC technology, especially for heavy-duty transportation such as trucks, is seen as a pivotal contributor to this transition due to its suitability for high energy demands and long-range requirements. As battery-electric solutions face challenges in these areas, FCs emerge as a viable alternative, offering the power and range necessary for such applications while maintaining zero-emission operation.

Germany is taking the lead within Europe, with considerable investments in FC technology, policies fostering its adoption, and a strong industrial base to support production and deployment. The German government has set ambitious targets for hydrogen and FC deployment and is actively promoting the integration of FCs in various modes of transport, including trucks.

The European FC market is projected to grow significantly, with estimates suggesting a jump from USD 2.52 billion in 2024 to USD 9.75 billion by 2029, growing at a compound annual growth rate (CAGR) of 31% [18]. The growth is driven mainly by the transportation sector, which is expected to dominate the market in the coming years. The prohibition on selling new gasoline and diesel cars starting in 2035 is expected to stimulate the growth of FCVs. Key market trends indicate a surge in hydrogen production and infrastructure development, creating substantial opportunities for the European FC market. In Germany, the number of hydrogen refueling stations has increased markedly, reflecting the country's dedication to developing a comprehensive hydrogen infrastructure to support the widespread adoption of fuel-cell vehicles, including trucks. The Europe FC industry is moderately concentrated, with significant players such as Ballard Power System Inc, Toshiba Corp, FC Energy Inc, Plug Power Inc, and Nuvera FC LLC leading the market. These companies are at the forefront of FC innovation, with several new developments such as the approval of substantial public funding for hydrogen projects and collaboration on FC system development for long-haul trucks, underscoring the market's dynamic nature.

In conclusion, the European market for ZEVs is on an upward trajectory, with a keen focus on hydrogen FC technology as a cornerstone for achieving greener transportation. With the backing of government policies, the establishment of essential infrastructure, and strategic industry partnerships, Europe is well-positioned to accelerate the adoption of ZEVs and significantly contribute to reducing greenhouse gas emissions in the transportation sector.

2.4 United States and California

In the United States, the adoption of ZEVs for MD/HDVs is gaining momentum, particularly in California, which often leads the country in environmental policies. The Advanced Clean Trucks (ACT) regulation [19], adopted by California, requires manufacturers to sell an increasing percentage of ZETs starting from 2024. This ambitious policy aims to transition to a fully electric commercial vehicle fleet over the next few decades. Federal incentives and a growing interest in reducing dependency on fossil fuels are supporting this shift. Other states are beginning to follow California's lead, indicating a broader national movement towards ZEV adoption in the commercial sector.

The adoption of MD/HD-ZEVs in California represents a progressive shift towards sustainability in the transportation sector that has traditionally relied on fossil fuels. This market encompasses a variety of vehicles—primarily buses, trucks, and delivery vans—each contributing to the reduction of carbon emissions. According to data for 2022, the total number of MD/HD-ZEVs stood at 2,320 [20]. Of these, buses led the count with 1,708 vehicles, followed by trucks at 272, and delivery vans at 340. Among all the sales, 134 buses were sold in the category of FCETs; all others are BETs.

California's commitments to alternative fuels in the transportation sector are exemplified by its network of hydrogen refueling stations, an essential infrastructure for FC MHDVs. According to information provided by the Hydrogen Fuel Cell Partnership [21], there are currently three transit-operated hydrogen refueling stations open to the public and five mixed-use stations planned by the California Energy Commission [22]. This infrastructure will support a growing fleet of hydrogen FC vehicles. The development of this infrastructure is strategic, enabling larger vehicles such as buses and delivery trucks to integrate into the zero-emission fleet. This support for hydrogen fuel technology signals California's multi-faceted approach to achieving its environmental goals, addressing passenger cars and larger vehicles that have a significant impact on transportation sector emissions.

3 Market feasibility issues for fuel cell electric trucks

As indicated in Section 2, development and sales of battery-electric trucks are progressing much faster, as of 2023, than FCETs are, and the expectation of most experts is that this will continue at least in the near-term. The reasons for this thinking is that FCET vs. BET market feasibility faces a number of challenges. These challenges are listed in Table 1. However, MD/HD FCETs do have some advantages over BETs that can and will be exploited as FC system technology matures and hydrogen refueling infrastructure is built. These advantages are also listed in Table 1. Some of the advantages of BETs are not technology related. Those advantages include the ready availability of electricity and many large electric utility companies that can connect battery chargers to the grid. Furthermore, large investments in battery R&D and manufacturing facilities to support the consumer electronics markets have resulted in large improvement in the performance of lithium-ion batteries and a rapid reduction in their cost. Hydrogen FCETs have had neither of these advantages and FC development and hydrogen production and distribution for vehicles has received relatively little investment, primarily from the Federal government. This situation seems likely to change in the future. Various aspects of likely changes in the market conditions for FCETs are considered in detail in Sections 4, 5, and 6.

Table 1. Market Feasibility Challenges and Technological Advantages of MD/HD FCETs.

Challenges	Advantages
Very high cost and very few models on the market.	Achieving long range (>300 miles) increases vehicle cost less for FCETs than for BETs.
Large truck manufacturers show little interest in developing FCETs.	Better acceleration and braking than ICE trucks and as much as BETs.
BETs are being developed by large and small truck manufacturers.	FCs may be more durable (longer life) than batteries for truck applications, requiring battery recharge nearly every day.
Low acceleration and braking performance compared to BETs	Cost of providing infrastructure for large fleets is less for FCETs than for BETs.
Very little refueling H2 infrastructure available for large trucks.	For trucks in regional applications, private terminals can be used for H2 refueling and reduce the dependence on the development of public H2 stations.
High price of dispensed hydrogen and very limited H2 supply for vehicle applications	Combined development of public highway H2 refueling stations for cars and trucks can provide highway refueling at reduced cost.
High cost of FCs and H2 storage on-board trucks..	H2 refueling time for FCETs is much less than charging time for BETs.
Difficult to make smaller trucks lower cost than comparable BETs with low battery cost.	Cold and hot weather operation of FCETs is less difficult than for BETs.
Few companies are developing FCs and associated systems.	Onboard storage is smaller, lighter, and lower cost for FCs and H2 than for batteries, making FCET vehicle design more similar to diesel vehicle design.
Markets for MD/HD trucks are relatively small, which will result in a longer time (yrs) for FC development and reductions in manufacturing costs.	Fleet operation for FCETs compared to BETs is more similar to fleet operation for diesel trucks than is the case.
FCET development costs are very high and difficult for start-up companies to cope with.	Storing large quantities of energy (>500 kWh) as hydrogen is more convenient and less costly than electricity in batteries.
Diesel engines and trucks have high efficiency (high mpg) resulting in FCETs having a relatively small energy (kWh/mi) advantage over diesel trucks and much less advantage than BETs.	Providing hydrogen refueling through liquid hydrogen stations equipped with cryo-pumps is less costly than providing battery charging.

4 Fuel cell system technology updates and projections

Recent technological advances have improved fuel cell system performance and efficiency. Advanced materials and manufacturing techniques have produced lighter, more compact fuel cell stacks and hydrogen tanks. Carbon fiber–reinforced composites have reduced hydrogen tank weight while maintaining high storage capacity and safety. Innovations in catalyst materials and membrane technology have created more efficient, durable FC stacks with higher power densities and longer lifetimes. Advances in battery technology, such as solid-state batteries and ultra-capacitors, have yielded compact, efficient energy storage solutions for rapid power delivery during acceleration and braking. These improvements support modern automotive demands, promoting sustainable and efficient fuel cell vehicles. Future research aims to further reduce weight, volume, and costs, leading to even more compact, efficient, and economically viable fuel cell systems, accelerating the transition to a hydrogen-based transportation ecosystem.

In this section, recent and future developments for various components in the system as it matures are discussed. These developments include (1) reductions in the weight (kg/kW) and volume (L/kW) of FC stack and hydrogen and air supply systems, (2) reductions in the weight (kg tank/kgH2) and volume (L tank/kgH2) of the hydrogen tank onboard the vehicle, and (3) reductions in the weight and volume of the electrical energy storage unit needed to provide the short peak power pulse for vehicle acceleration and braking.

4.1 FC weight and volume

Development to reduce the weight and size of the proton-exchange membrane (PEM) FC stack and associated air supply system is on-going for automotive and heavy-duty FC systems. Continuous progress [23-28] has been made for both LD and HD truck and bus applications. As shown in Table 2, the weight (kg) and volume (L) of the FCs are considerably smaller than those designed for use in HD vehicles for the same 100 kW FC system. Both types of FCs are currently (2024) being used in commercially available vehicles by Toyota and Ballard. FCs in HD vehicles have to operate at high power much of the time and need to be designed to have a much longer duration lifetime (hrs) at those high powers. As a result, it is expected that the weight and volume per kW (kg/kW and L/kW) of the HD FCs will be significantly higher than those of the LD FCs. It is difficult to project the size characteristics of the LD and HD future FC systems, but based on past progress, a reduction by a factor of at least 2 from present kg/kW and L/kW values in the future would seem to be likely. This reduction in size is assumed in calculations of FC characteristics in this report.

The weights and volumes of the battery and FCs in long haul ZEVs with ranges of 300 miles and 500 miles using 2025 and 2035 technology are shown in Table 2. The large advantage of the FC in long haul applications is evident in the table, even when high energy density batteries are used in 2035.

Table 2. Weights and volumes for battery-electric and FC long haul trucks.

	Range miles	Battery Wh/kg	Battery kWh	Battery kg	Battery L	H2 kg	FC kg	FC L
2025	300	225	788	3500	1575	33	500	1250
	500	500	1312	5832	2625	56	500	1250
2035	300	350	675	1543	865	26	250	625
	500	780	1125	2571	1441	42	250	625

350 kW electric motor, Battery$_{SOC}$ final =.2, 250 kW FC, H2SOCfinal=0.1

4.2 Weight and Volume of the on-board hydrogen storage unit

The unit onboard the vehicle to store the hydrogen is much heavier and larger than the fuel tanks on diesel trucks. As a result, determining its weight (kg) and volume (L) are important factors in comparing hydrogen FCETs with battery-electric and diesel trucks of various classes. Hydrogen can be stored as a high pressure gas or as a cryogenic liquid. The physical characteristics of the H2 stored are shown in Table 3.

Table 3. Densities and energy of compressed gas and liquid hydrogen.

Hydrogen phase	Temperature deg K	Pressure atm	Density Kg/L	Energy MJ/kg
Compressed gas	300	350	0.0235	10.2
Compressed gas	300	700	0.0387	18.5
Liquid	15-20	.5-2	0.071	30-40
Compressed- cryogenic liquid	25	300	0.08	< 1

The tanks for storing the H2 are usually characterized in terms of kgH2/kg tank and kgH2/L tank. There has been much R&D in recent years to reduce the weight, volume, and cost of the onboard unit. Compressed gaseous hydrogen is stored at 350 or 700 bar in a composite tank consisting of a liner of a high density plastic wrapped with carbon fiber reinforced with epoxy resins. The technology for the high pressure H2 tanks is mature and the major R&D activity is to reduce the cost of the carbon fiber. The characteristics of the onboard H2 storage units are shown in Table 4. The technology for storing the hydrogen onboard as a cryogenic liquid is not mature and only 1-2 commercial products are currently available (see **Figure 1**).

Table 4. Characteristics of onboard vehicle hydrogen storage systems.

Hydrogen phase	kgH2/sys kg	kgH2/L sys	$/kgH2
DOE goal 2025	0.055	0.04	500
DOE Goal ultimate	0.065	0.05	300
Compressed gas 350 bar	0.045	0.016	433 (high volume-2015)
Compressed gas 700 bar	0.042	0.027	566 (high volume 2015)
LH2 Liquid 20-50 deg K 0-20 bar	0.116	0.041	NA
Compressed liquid 300 bar	0.072	0.044	

Figure 1. An onboard cryogenic H2 storage tank from Chart Industries [29].

The Chart Industries unit stores 35 kg of hydrogen and is sized to replace the standard diesel fuel tank placed along the side rails of the tractor of the long-haul truck. Two of the H2 storage units can store 70 kg. Each storage unit weighs about 300 kg and has an external volume of 850 L. For a truck that uses 0.095 kgH2/mi, the daily range for the 70 kg capacity would be over 700 miles, which is comparable to a diesel truck. The Chart Industries LH2 storage unit meets the DOE goals and does not require compression of the hydrogen to high pressure at the refueling station. The unit has been tested successfully by several truck manufacturers in FC long haul trucks.

4.3 Electric powertrain power and energy storage capacity

The electric driveline of the FCET consists of the electric motor, power electronics, and power battery, in addition to the FC. The power battery provides the electrical energy to the electric motor when the power output of the FC is not sufficient to meet the truck demand. The power battery also stores the energy generated during regenerative braking. For acceleration and braking, power demands are in pulses of 10–40 seconds, whereas for gradeability, the power demand is steady.

At present, the power battery is sized (kWh) to meet the power demand of the electric motor (kW) during accelerations and the energy needed for driving up short steep grades (4-5%). The FC in the truck is often not sized (kW) to meet the vehicle power demand during the acceleration and gradability periods of driving. Table 5 shows the power and energy demands for trucks of various classes to meet acceleration and gradeability demands. The maximum power capability of power batteries as a function of energy stored (kWh) is shown in Table 6. Except for Class 8 long haul trucks, the power demands for accelerations dominate and the demands for gradeability are much lower. In the case of the Class 8, long haul trucks, the power demand on steep, highway grades is slightly higher than for accelerations. The FC system power (kW) for trucks is usually 200 kW or less and it is used as steady power. Hence only the power for acceleration needs to be met by the power battery alone and the power battery can be sized to meet the acceleration, pulse power demand. This design approach allows for optimizing the power battery to handle pulse power demands during acceleration, ensuring the truck's performance and efficiency. Future advancements are expected to further optimize the sizing and integration of these components, enhancing the overall performance and capability of FCETs across applications.

Table 5. Power and energy demands for truck acceleration and gradeability.

	Power (kw)					Energy (kWh)
Truck class & weight	**Acceleration 0-60 mph, sec**	**Acceleration 0-60 mph**	**Cruise 65 mph**	**4% grade 40 mph**	**5% grade 55 mph**	**5% grade, 4 mile**
Class 8 LH 37,000 kg	35	383	160	260	446	32.4
Class 6 10,000 kg	15	240	68	70	120	8.7
Class 4 7500 kg	12	225	55	53	90	6.5
Class 3 6500 kg	10	235	53	46	78	5.7

Table 6. Power capability of the power battery.

Battery storage (kWh)	Battery weight* kg	Max. power* kW
10	50	75
20	100	150
30	150	225
40	200	300
50	250	375
60	300	450
70	350	525

*200 Wh/kg, 1500 W/kg

The power demand for acceleration can be met by the power battery alone or with a combination of a battery and supercapacitor. The characteristics of energy storage devices that could be used to meet the acceleration power demand are shown in **Table 7**. They include lithium-ion batteries of various chemistries, electrochemical double layer capacitors (EDLC) carbon/carbon supercapacitors, hybrid supercapacitors, and a superbattery being developed by Skeleton Technologies [30,31]. The power energy storage unit must provide the high, pulse power to the electric motor as well as store sufficient energy to accelerate the vehicle to at least 60 mph. For Class 8, fully loaded trucks, the energy storage requirement is about 4 kWh. This requirement will preclude the use of EDLC supercapacitors in the Class 8 trucks, but as discussed by Burke and Miller [32], they could be used in LD FCV and some smaller MD trucks. For HD applications, the power energy storage unit can be a lithium titanate oxide (LTO) battery, a hybrid supercapacitor, or the Skeleton super battery. These high power devices could be combined with an energy-type nickel manganese cobalt (NMC) lithium-ion battery to form an optimum energy storage unit for the HD FCV.

Table 7. Energy storage device characteristics.

	Energy density (Wh/kg, kg/L)	Power density W/kg (90% eff.).	Power/energy (W/Wh)	Cost ($/kWh)
Battery chemistry				
NMC	165, 2.4	1100	6.7	100
NMC	115, 2.4	2070	18	200
LFP	110, 2.2	1135	10	100
LFP	110, 2.2	1640	15	250
LTO	90, 1.9	740	8	400
LTO	35, 1.9	2100	60	600
Supercapacitors				
Skeleton 3200F EDLC	8.9, 1.4	3460	390	1528
Skeleton 5000F EDLC	8.4, 1.4	3550	422	1619
Skeleton 4100F EDLC	4.9, 1.4	2860	583	2775
Aowei 10,000F hybrid	40, 1.8	2250	56	340

The characteristics and cost of a power unit using the LTO battery, the hybrid supercapacitor, or the superbattery for powers of 300, 400, and 500 kW are given in Table 8. The cycle life of the LTO battery can be about 10,000 cycles [33,34]. The cycle life of the hybrid supercapacitor is claimed to be 500,000 cycles. The cycle life of the superbattery is uncertain, because it is a new development, but its construction and materials are much like those used in Skeleton supercapacitors [35-37]. All units shown in Table 8 could be combined with a 25 kWh NMC lithium in the HD FCET. The acceleration and braking performance of the FCET would be as good as the BET and much better than the comparable diesel truck.

Table 8. Characteristics of power units for HD FC vehicles.

Peak power kW	LTO battery alone*	Hybrid supercap**	Superbattery***
300	143 kg, 5kWh, Cost $3k	133 kg, 5.3 kWh, cost $2k	94 kg, 4.2 kWh Cost $1.9k
400	190 kg, 6.7 kWh, cost $4k	178 kg, 7.1 kWh, cost $2.4	125 kg, 5.6 kWh Cost $2.5k
500	238 kg, 8.3 kWh, cost $5k	222 kg, 8.9 kWh Cost $3k	156 kg, 7.0 kWh Cost $3.2k

*35 Wh/kg, 2100 W/kg, $600/kWh, **40 Wh/kg, 2250 W/kg, $340/kWh, *** 45 Wh/kg, 3200 W/kg, $450/kWh

5 Zero-emission truck cost

5.1 Initial vehicle cost

The FCET model has been configured to accommodate six distinct types of MD/HD trucks. These include Class 3 city delivery vans, Class 4 step delivery trucks, Class 5 step vans, Class 6 box trucks, Class 7 short-haul trucks, and Class 8 long-haul trucks. We used the Advanced Vehicle Simulator (ADVISOR) software to simulate each type of ZEV truck alongside baseline diesel vehicles, with varying inputs to reflect technological improvements projected for the period from 2020 to 2040. The energy consumption, expressed as kgH2/mi for the FCETs, was derived from these ADVISOR simulations. A detailed configuration of the powertrains of the trucks was used in the cost analyses. These analyses involved the integration of detailed efficiency maps for prime movers such as engines and electric motors. The ADVISOR software emulates vehicle operation over urban and highway driving cycles including the inputs of aerodynamic drag coefficients and tire rolling resistance. ADVISOR uses an array of inputs and dynamic interactions to generate a range of results. These results include critical metrics of fuel efficiency, total energy usage, and, when applicable, emissions output. These metrics provide an in-depth understanding of the environmental impact and performance efficiency of each vehicle type across numerous driving cycles. Further details on ADVISOR modeling and its applications can be found in our previous studies [38]-[41].

5.2 Battery and fuel cell costs

Projecting battery and FC costs in terms of $/kWh and $/kW is complex and requires regular updates, affecting the costs used in ouranalyses. The necessity to revise our cost estimates upward from those posited in earlier papers has been influenced largely by a more detailed integration of the cells into modules, modules into the battery pack, and the markup of the pack in the vehicle. In the case of the FC system, the integration includes the system components into the vehicle and the markup of the system into the vehicle cost. The integration factors and markups that have been added reflect a better understanding of the indirect costs such as installation, maintenance, and the system integrations required for operational efficacy of the vehicles. Our vehicle costs are higher than previously reported and this will impact our market share projections later in this report. The updated battery and FC costs for MD/HD ZEV trucks are discussed below.

5.2.1 Battery costs

Considerable academic research has been dedicated to examining the trajectory of battery costs over the forthcoming decade. This includes a detailed evaluation of the limits to battery cost reductions [42], along with innovations in materials and manufacturing that benefit from economies of scale [43]. Additionally, the application of multifactorial learning curves has been employed to predict the pricing trends of lithium-ion NMC battery packs [44]. Research has also delved into the electro-thermal characteristics, aging patterns, and economic factors of LTO cells in high-power automotive settings [45]. Further studies have refined this model by integrating input costs to more accurately reflect technological advancements during the energy transition [46]. A comprehensive review synthesizing 360 data points from these studies presents a cost trajectory for battery packs, projected to decrease to around $70 per kilowatt-hour by 2050, as shown in Figure 2 [47]. This review also highlights 12 forecasts for specific technologies, suggesting potential costs under $90 per kWh for cutting-edge lithium-ion batteries and $70 per kWh for lithium-metal variants. The ongoing research signals a promising decline in battery prices, influenced by consistent technological advancements rather than fluctuations in raw material costs. Nevertheless, persistent uncertainties related to cost and technological maturation continue to challenge researchers and industry stakeholders.

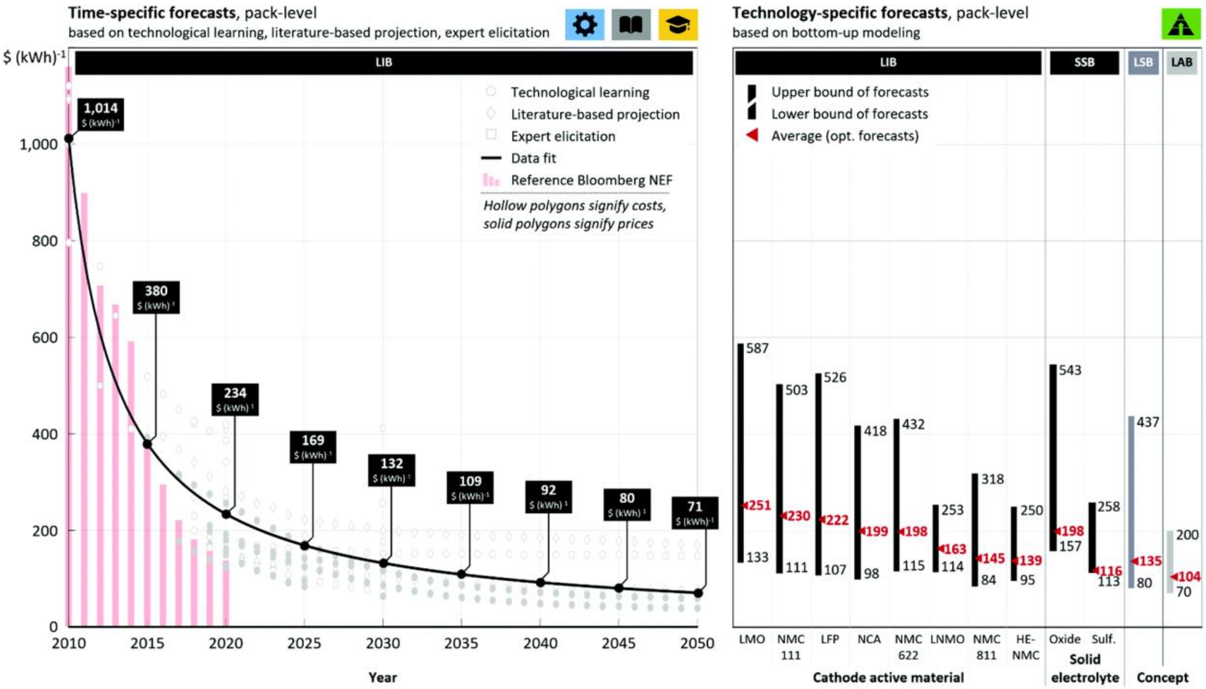


Figure 2. Battery pack cost estimations. Copyright 2021, Royal Society of Chemistry [47].

The latest results of battery costs used in our study are shown in **Table 9**. The battery pack costs align with the holistic trend across academic projections as depicted in **Figure 2**. In addition to the pack manufacturing cost, two other factors contribute to the showroom cost of the battery system: the pack-to-vehicle integration factor and the battery system markup.

(a) Pack Manufacturing Cost: This is the base cost of producing the battery pack itself. It includes the costs of materials (such as lithium and cobalt), labor, and overheads associated with manufacturing each battery unit. It forms the foundational expense in the overall cost structure of a battery system.

(b) Pack-to-Vehicle Integration Factor: This factor refers to the additional costs incurred when integrating the battery pack into a vehicle. It covers the engineering, design, and labor needed to securely and effectively install the battery into the specific design and system architecture of the vehicle. This integration ensures that the battery operates efficiently and safely within the vehicle, coordinating with other hardware and software-related vehicular systems such as the electronic control unit, the thermal management system, and the battery management system.

(c) Battery System Markup: This represents the profit margin added by the manufacturer or distributor on top of the cumulative production and integration costs. The markup covers various indirect costs such as market feasibility, sales, and administrative expenses, and contributes to the company's profitability. It also accounts for research and development costs for future technological advancements.

Table 9. Battery costs for battery-electric trucks between 2020 and 2040.

Battery cell cost ($/kWh)*	2020	2025	2030	2035	2040
High cost case	180	149	124	103	85
Base cost case	160	133	110	91	76
Low cost case	140	116	96	80	66
Cell-to-pack integration factor	1.45	1.33	1.25	1.20	1.18
Pack-to-vehicle integration factor	1.60	1.47	1.38	1.33	1.30
Battery system markup	1.35	1.35	1.35	1.35	1.35
Battery system cost (before integration into BET - base)	313	239	187	149	121

*Battery cell costs to OEMs.

5.2.2 Fuel cell costs

Wang et al. (2022) reported that the cost of a proton exchange membrane fuel cell (PEMFC) stack is around $75 per kilowatt (kW) at high production volumes. Catalyst layers (CLs), which use costly platinum-group metals (PGMs) as catalysts, account for over 40% of the stack's total cost [48]. **Figure 3** illustrates the projected cost trends for hydrogen FC units spanning from 2020 to 2040 [49]. The dashed line represents the cost estimate from the International Council on Clean Transportation (ICCT), which is derived from an amalgamation of primary research data and secondary sources. The method used to construct the ICCT cost curve assigns double the weight to primary research compared to secondary sources, ensuring a more data-driven approach to the forecast. More detailed information can be found in the ICCT report.

The cost modeling for the heavy-duty FC system according to the US Department of Energy (DOE) Hydrogen Program Record is depicted in **Figure 4** [50]. It has been conducted based on an annual production of 50,000 units, establishing the cost benchmarks for 2022. The intermediate target for 2025 remains at this production level, while the targets for 2030 and beyond are set with an expectation of increased production volumes of 100,000 units per year. As of 2022, the cost stands at \$179 per kilowatt (kW), reflecting an 8% reduction from the 2021 figure of \$196/kW at the same production rate. Notably, developers of medium-duty and heavy-duty FC stacks are innovating with modular system designs that facilitate the use of a unified platform across multiple vehicle applications, thereby achieving significant economies of scale. In 2020, sales of MD and HD diesel trucks in the U.S. totaled 167,000 and 243,000 units, respectively, supporting the feasibility of ramping up to a production volume of 50,000 to 100,000 FC systems annually, particularly as stack standardization across models progresses. The anticipated cost for 2025 is projected at \$140/kW$_{net}$, decreasing further to \$80/kW$_{net}$ by 2030, and ultimately to \$60/kW$_{net}$, driven by ongoing technological advancements and increased production efficiencies.

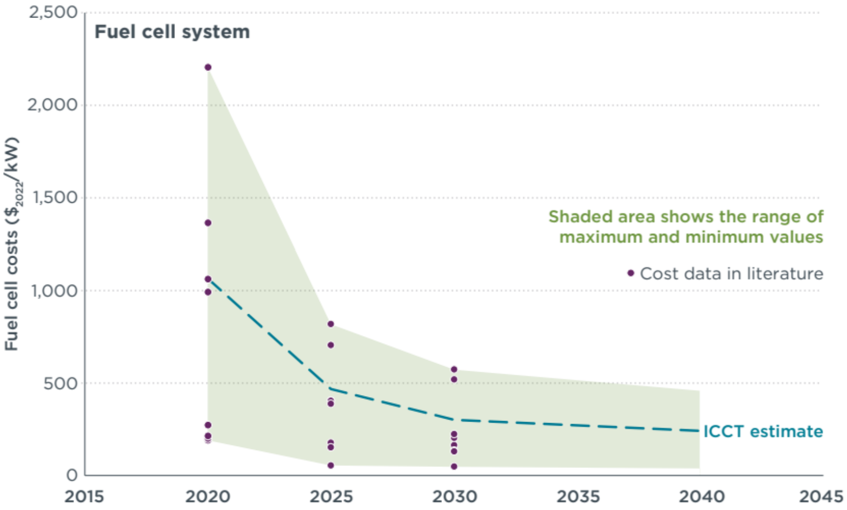


Figure 3. Estimated manufacturing cost of energy batteries by ICCT [49].

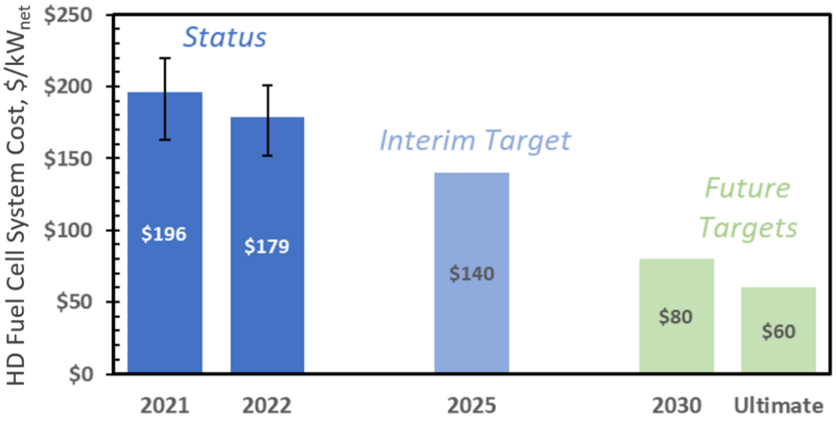


Figure 4. DOE Heavy-duty FC System Cost Status Interim Target [50].

Figure 5 illustrates the anticipated decline in fuel cell system costs for FC buses (projected by Ballard), indicating a drop from $1,500 per kW in 2019 to $600 per kW by 2029. This trend reflects improvements in manufacturing and economies of scale, driven by technological advancements. While the material costs for these systems remain relatively low, the manufacturing expenses are initially high due to complex technology. However, as production scales up and technological efficiencies are gained, significant reductions in both the purchase and parts replacement costs are expected, making fuel cell systems more economically viable for broader applications. Furthermore, applying an exponential curve based on Ballard's data projects that the cost of the fuel cell system will decrease to $319/kW.

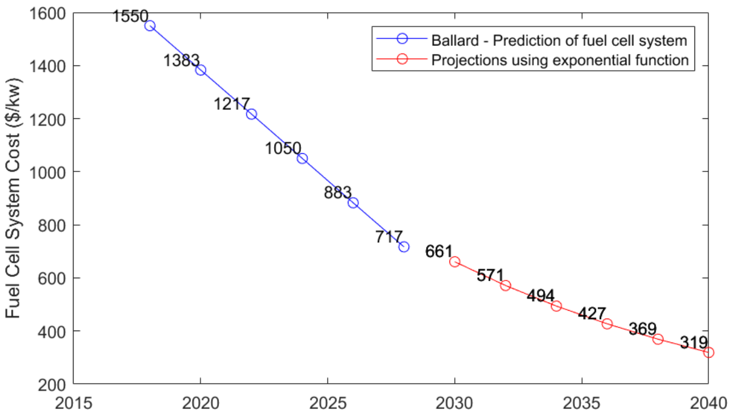


Figure 5. Ballard’s forecast of fuel cell system for FC buses [51].

To make FCETs competitive in terms of price, target costs are set at $60 per kW for heavy-duty vehicles. FC costs are expected to decrease significantly as system and manufacturing technologies advance, similar to the trends observed with lithium batteries over the past decade. However, the rate of cost reduction for FCs might be slower due to potentially lower production volumes compared to lithium batteries, where cost reductions benefitted from the massive scale-up of production in China and Korea and substantial governmental support in China for EV adoption. For the economic evaluation presented in this study, three scenarios for FC costs—high, base, and low—are considered to model different market development trajectories. The high-cost scenario assumes slow market growth, whereas the low-cost scenario predicts faster market expansion, potentially driven by major automakers pivoting towards FCETs rather than BETs. The various cases (high, base, and low), representing the different market scenarios, along with projected costs for each scenario, is detailed in **Table 10**.

Table 10. Fuel cell costs for fuel cell electric trucks between 2020 and 2040.

Unit cost ($/kW)	**2020**	**2025**	**2030**	**2035**	**2040**
High cost case	400	300	225	169	127
Base cost case	300	225	169	127	95
Low cost case	200	150	113	84	63
FC-to-vehicle integration factor	2.00	1.90	1.80	1.71	1.63
FC system markup	1.35	1.35	1.35	1.35	1.35
FC system cost (before integration into FCET - base)	1944	1111	636	363	208

5.2.3 Projected vehicle costs for HD long haul ZEV trucks

5.2.3.1 Analysis of the initial cost of the BETs

For the battery EVs, the initial vehicle cost is given by

$$(\text{Vehcost})_{\text{BET}} = \text{glider} + \text{Electric drive cost} + \text{battery cost} \qquad \text{Eq. 1}$$

$$\text{Glider} = \text{Price Diesel Vehicle} - \text{cost of engine and transmission of the diesel vehicle} \qquad \text{Eq. 2}$$

$$\text{Electric drive cost} = \$/\text{kW} \times \text{kW of EM} \times \text{system integration factor } (\text{IF}_{\text{pt}}) \text{ for the driveline} \qquad \text{Eq. 3}$$

$$\text{Battery kWh} = (\text{kWh/mi})_{\text{level}} \times \text{bat. oversize factor } (\text{OSF})_{\text{bat}} \times \text{minimum range requirement (miles)} \qquad \text{Eq. 4}$$

$$\text{Battery cost} = \text{Battery kWh x } (\$/\text{kWh})_{\text{bat}} \times \text{system integration factor } (\text{IF}_{\text{bat}}) \text{ for the battery pack} \qquad \text{Eq. 5}$$

5.2.3.2 Analysis of the initial cost of the FCETs

For the hydrogen FC vehicles, the initial vehicle cost is given by:

$$(\text{Vehcost})_{\text{H2 FC}} = \text{glider} + \text{Electric drive cost} + \text{Power battery cost} + \text{FC system cost} \qquad \text{Eq. 6}$$

$$\text{FC cost} = \$/\text{kW} \times \text{kW of FC} \times \text{integration factor} \qquad \text{Eq. 7}$$

$$\text{hydrogen storage cost} = \$/\text{kgH}_2\text{stored} \times \text{kg stored H}_2 \times \text{integration factor} \qquad \text{Eq. 8}$$

$$\text{kg stored H}_2 = (\text{kg/mi})_{\text{on level}} \times \text{H}_2 \text{ oversize factor} \qquad \text{Eq. 9}$$

$$\text{FC system cost} = \text{FC cost} + \text{hydrogen storage cost} \qquad \text{Eq. 10}$$

$$\text{power battery cost} = (\$/\text{kWh})_{\text{powerbat}} \text{ x } (\text{kwh})_{\text{powerbat}} \times \text{integration factor} \qquad \text{Eq. 11}$$

The H2 oversize factor is conceptually similar to the battery oversize factor and is a correction to the simplistic calculation of energy needed on a given drive cycle to drive a given range. The increase is due to vehicle hotel (accessory) loads, road grade, and other factors that can increase the power demands.

The hydrogen oversize factor is lower than the battery oversize factor because there is no correction for degradation over time, or sizing to ensuring a minimum cycle life.

Table 11 and **Table 12** provide the inputs for Class 8 long-haul FCETs and their BET counterparts. For BETs, the battery system will remain the most expensive component for a significant period. For MDTs, the battery system—after factoring in integration elements such as cell-to-pack and pack-to-vehicle integration, as well as cost markups—currently accounts for around 55% of the total vehicle cost. This figure is projected to decrease to approximately 45% by 2040. For HDTs, particularly Class 8 long-haul trucks, the battery system represents 60-75% of the total vehicle cost, depending on driving range requirements and markup factors. This percentage is not expected to fall below 50% before 2035, due to the need for large battery packs to achieve a 500-mile pure electric range. In contrast, when evaluating FCETs, our vehicle cost model indicates that for MDTs, the fuel cell system—considering factors such as fuel cell-to-vehicle integration and cost markups—accounts for about 40% of the total vehicle cost before 2030, with a potential reduction to 30% by 2040. For Class 8 long-haul trucks, the fuel cell system is projected to make up around 20% of the total vehicle cost over the next two decades. Hydrogen storage, which is critical for FCETs and typically involves high-pressure composite tanks, also plays a significant role in vehicle costs. For Class 3 to Class 7 FCETs, the hydrogen storage system currently accounts for approximately 10% of the total vehicle cost, with a potential reduction to about 5% by 2040. In Class 8 long-haul FCETs, this figure ranges from 35% in 2020 to 15% by 2040 due to the larger storage requirements.

Table 13 and **Table 14** show the projected costs for FCETs and BETs, respectively, within the class 8 long-haul truck category. The costs for ICEVs are presented in **Table 15**. The cost comparisons (**Figure 6**) indicate that neither FCETs nor BETs are likely to achieve cost parity with ICEVs by 2040. Both FCETs and BETs incur somewhat higher costs than ICEVs do in the MDT market segment. In the Class 8 long-haul truck market, FCETs have a greater possibility than BETs of achieving cost parity with ICEVs in the coming decade, especially for ranges of 400 miles or more. For ranges exceeding 500 miles, the cost of FCETs is significantly lower than that of BETs. In the long term (2030-2040), FCETs have the potential to be substantially more cost-effective than BETs across all mileage ranges, particularly with mass hydrogen production.

Table 11. Data inputs for a fuel cell class 8 short-haul truck, base case.

Year	Electric motor power (kw)	FC power (kw)	Battery capacity (kwh)	Glider cost ($)	Electric drive (/kw)	Electric drive integration markup factor	Electric motor cost markup	FC ($/kw)	Fuell cell cost markup	FC integration	H2 storage (/kgH2)	H2 storage markup	Power battery cost ($/kwh)	Battery markup
2020	350	200	25	130,000	75	1.80	1.35	300	1.35	2.00	1,400	1.35	300	1.35
2025	350	200	25	133,000	56	1.62	1.35	225	1.35	1.90	800	1.35	200	1.35
2030	350	200	25	137,000	42	1.46	1.35	169	1.35	1.81	400	1.35	175	1.35
2035	350	200	25	138,000	32	1.31	1.35	127	1.35	1.71	350	1.35	150	1.35
2040	350	200	25	138,000	24	1.18	1.35	95	1.35	1.63	300	1.35	125	1.35

Table 12. Data inputs for battery-electric class 8 short-haul truck, base case.

Year	Electric Motor Power (kW)	Glider Cost ($)	Electric Drive (/kW)	Electric Drive Integration Factor	Electric Motor cost markup	Energy Battery ($/kWh)	Battery cost markup	Cell to Pack integration factor	Pack to vehicle integration factor
2020	350	130,000	75	1.40	1.35	160	1.35	1.45	1.60
2025	350	133,000	56	1.33	1.35	133	1.35	1.33	1.47
2030	350	137,000	42	1.26	1.35	110	1.35	1.25	1.38
2035	350	138,000	32	1.20	1.35	91	1.35	1.20	1.33
2040	350	138,000	24	1.14	1.35	76	1.35	1.18	1.30

Table 13. Projected costs for fuel cell electric trucks (Class 8 long haul truck, base case).

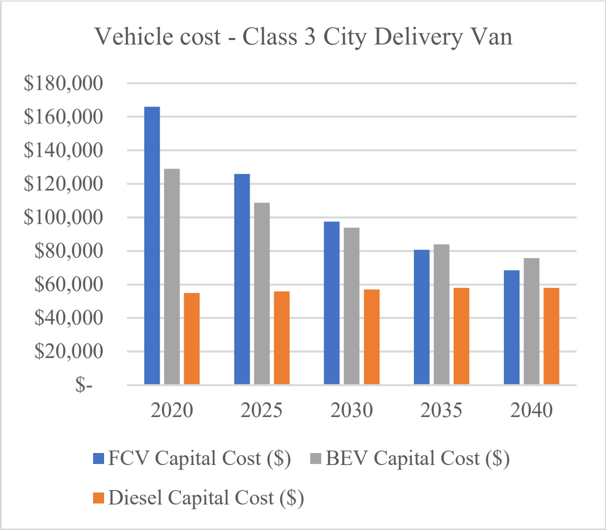
Year	Required Range (miles)	H2 Oversize factor	H2 capacity (kg)	Total Vehicle Cost ($)
2020	350	1.38	97	553,549
	400	1.38	110	579,631
	450	1.38	124	605,713
2025	400	1.38	99	408,207
	450	1.38	112	421,620
	500	1.38	124	435,034
2030	450	1.38	99	309,620
	500	1.38	110	315,582
	550	1.38	121	321,544
2035	500	1.38	97	267,965
	550	1.38	106	272,530
	600	1.38	116	277,094
2040	550	1.38	91	234,613
	600	1.38	99	237,966
	650	1.38	108	241,320

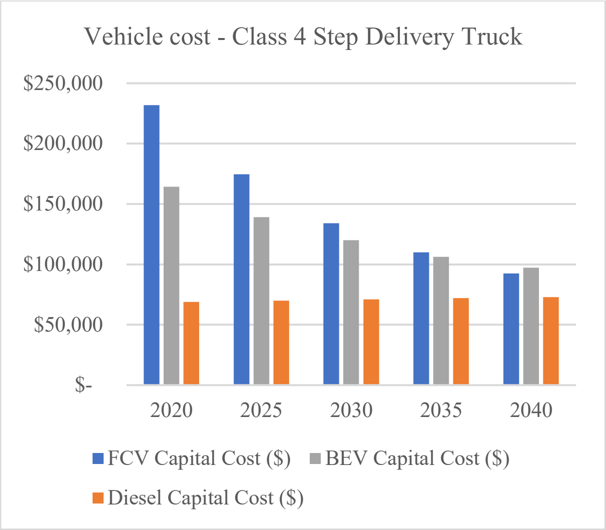
Table 14. Projected costs for battery electric trucks (Class 8 long haul truck, base case).

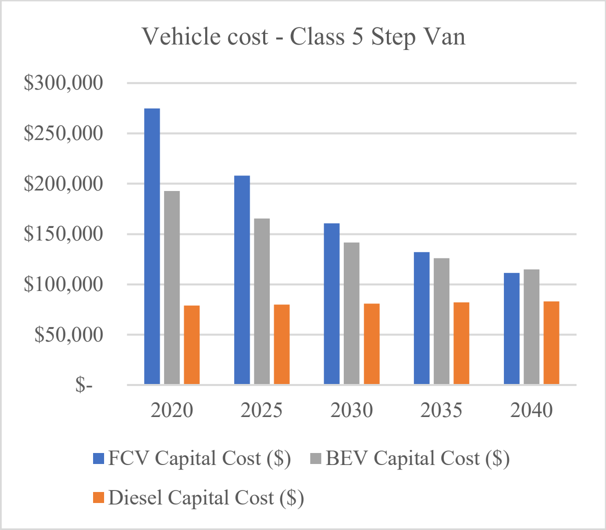
Year	Required Range (miles)	Battery Oversize factor	Battery capacity (kWh)	Total Vehicle Cost ($)
2020	300	1.38	903	631,883
	350	1.38	1053	707,262
	400	1.38	1203	782,640
2025	350	1.38	1014	525,426
	400	1.38	1159	576,437
	450	1.38	1304	627,448
2030	400	1.38	1121	451,497
	450	1.38	1261	487,661
	500	1.38	1401	523,824
2035	450	1.38	1217	396,325
	500	1.38	1352	423,033
	550	1.38	1488	449,742
2040	500	1.38	1297	355,001
	550	1.38	1427	375,422
	600	1.38	1557	395,844

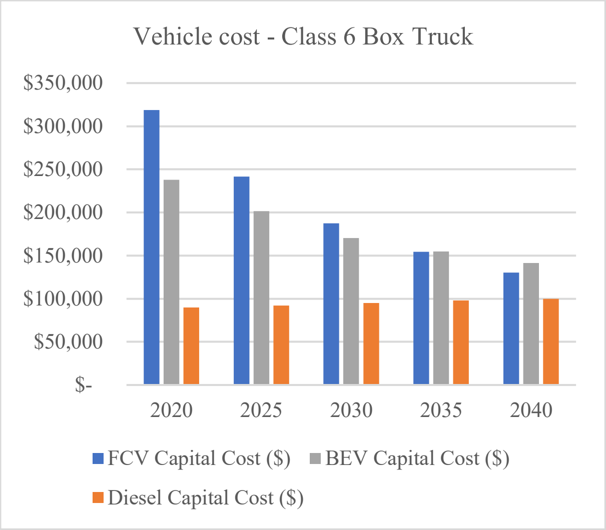
Table 15. ICEVs cost in Class 8 long-haul trucks.

Year	Cost ($)
2020	175,000
2025	180,000
2030	185,000
2035	190,000
2040	195,000


Vehicle cost - Class 3 City Delivery Van
$180,000
$160,000
$140,000
$120,000
$100,000
$80,000
$60,000
$40,000
$20,000
$-
2020
2025
2030
2035
2040
FCV Capital Cost ($)
BEV Capital Cost ($)
Diesel Capital Cost ($)


Vehicle cost - Class 4 Step Delivery Truck
$250,000
$200,000
$150,000
$100,000
$50,000
$-
2020
2025
2030
2035
2040
FCV Capital Cost ($)
BEV Capital Cost ($)
Diesel Capital Cost ($)


Vehicle cost - Class 5 Step Van
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$-
2020
2025
2030
2035
2040
FCV Capital Cost ($)
BEV Capital Cost ($)
Diesel Capital Cost ($)


Vehicle cost - Class 6 Box Truck
$350,000
$300,000
$250,000
$200,000
$150,000
$100,000
$50,000
$-
2020
2025
2030
2035
2040
FCV Capital Cost ($)
BEV Capital Cost ($)
Diesel Capital Cost ($)

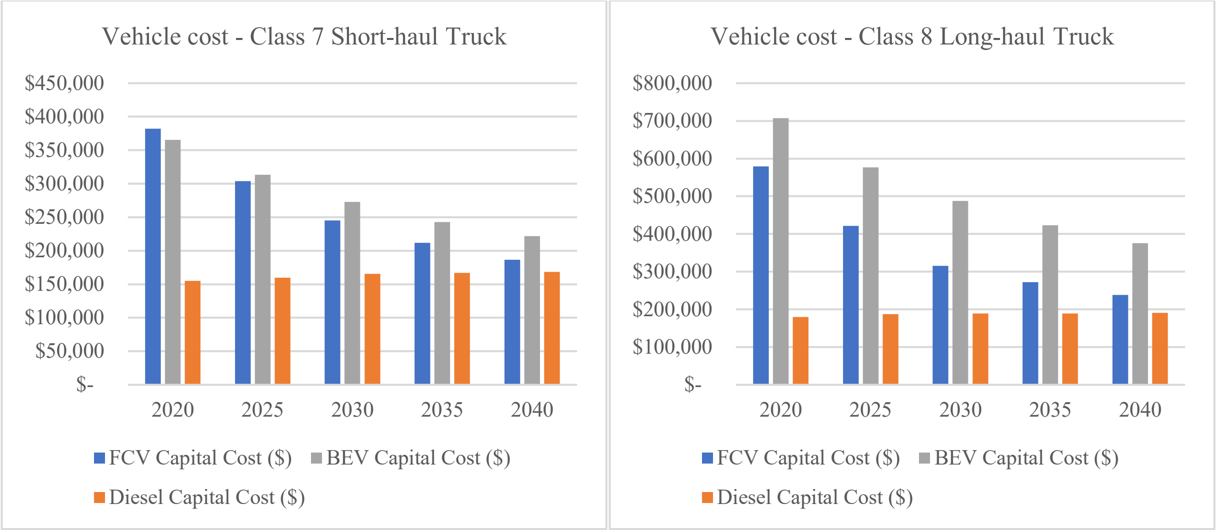


Figure 6. Vehicle costs of BETs and FCETs from class 3 to class 8.

5.3 Comparisons of truck cost projections

The literature offers limited insights into the projected costs of ZEV MD/HD trucks. Research into the projected costs for ZEV trucks has been carried out by several organizations, including the University of California, Davis (UCD), ICF International (ICF) [52], the California Air Resources Board (CARB) [53], the International Council on Clean Transportation (ICCT) [54], the National Renewable Energy Laboratory (NREL) [55], and Argonne National Laboratory (ANL) [56]. The truck cost projections are summarized in

Table 16 and **Table 17**, which show large variations in the cost estimates for these vehicles due to glider costs, battery sizes, and fuel cell costs. The available vehicle cost projections provide little consensus either on the vehicle costs or whether FCETs will have a lower cost than BETs until ranges of about 500 miles. The Department of Energy (DOE) [57] and the DOE National Laboratories are more optimistic than other groups concerning the cost of FCETs. In general, the cost ($/kW) of FC systems in 2030 and beyond remains uncertain. Further, the FC power (kW) needed in Class 7 and 8 FCETs and the size (kWh) of the power battery needed to support the FC are uncertain. These uncertainties can significantly affect the cost of the Class 8 long-haul FCETs.

Table 16. Cost comparisons for class 5 trucks.

Class 5 (US$, k)	UCD (base)	ICF	ICCT	CARB
ICE (2022)	80k	100k	85k	91k
BET urban				
2025	165k (150 miles)	N/A	N/A	113k
2030	141k (175 miles)	141k	75k	108k
FCET urban				
2025	208k (200 miles)	N/A	N/A	129k
2030	160k (225 miles)	N/A	150k	119k

Table 17. Cost comparisons for class 8 trucks.

Class 8 (US$, k)	UCD (base)	ICF	NREL	ANL	ICCT	CARB
ICE (2022)	165k	110k	135-146k	N/A	155k	N/A
BET long haul						
2025	576k (400 miles)	N/A	316	600	N/A	304k
2030	487k (450 miles)	191k	230-300k	N/A	260k	247k
FCET long haul						
2025	422k (450 miles)	N/A	N/A	260	N/A	251k
2030	316k (500 miles)	N/A	160-200k	153k	250k	226k

5.3.1 Battery electric trucks:

Glider costs and battery size: UCD estimates a significantly higher glider cost compared to others. This difference contributes to the overall higher vehicle cost forecasted by UCD. Additionally, UCD's projected battery size for BETs is oversized by a factor of 1.38 compared to ICCT's estimates. For instance, for a 500-mile range, ICCT anticipates a battery size of 1000 kWh (current technology) and 740 kWh (future technology), whereas UCD projects a need for 1400 kWh. This oversized estimation further escalates the BET costs in UCD’s analysis. Note, the battery minimum SOC and adjustments: UCD models a minimum SOC of 15-20% and includes an additional 25% capacity to accommodate grade and high-speed driving conditions, which is not similarly accounted for in ICCT’s model.

5.3.2 Fuel cell electric trucks

Fuel Cell Costs: For the year 2030, UCD's cost per kilowatt ($169/kW) is lower than that of ICCT ($301/kW). However, after considering the markup factor (1.35), the fuel cell cost will be $228/kW, aligning with a recent study that shows €204 ± 12/kW at the system level, based on 424 observations [58]. The disparity diminishes by 2040, with UCD forecasting $95/kW at the stack/unit cost and $128/kW at the system level. This variation in cost assumptions is a major factor driving UCD's higher fuel cell cost projections.

Hydrogen Storage: Similar to the approach used in BETs, we oversize the hydrogen storage capacity for FCETs by a factor of 1.2 to maintain a minimum SOC of 85 to 90%. This design choice, aimed at ensuring higher operational reliability and range, also contributes to the increased cost projections.

In short, the higher cost projections for both BETs and FCETs by UCD can be largely attributed to more conservative assumptions regarding vehicle and component sizing, as well as higher baseline costs for critical components such as gliders and fuel cells. These differences underscore the need for a detailed examination of the underlying assumptions in cost modeling, ensuring that they align with realistic expectations of technological advancements and market trends.

5.4 Total cost of ownership

To calculate the total cost of ownership (TCO) over specified periods of 5 or 15 years, it is necessary to tally the annual operating expenses throughout each year and then aggregate these costs. The methodology incorporates discounting future expenses using the formula $[1/(1+d)^{n-1}]$, where d is the discount rate and n is the corresponding year. For this analysis, the discount rates are set at 10% for the 5-year and 3% for the 15-year evaluations. Additionally, assumptions about the residual values of the vehicles and batteries are crucial. After 5 years, the residual value of the diesel truck is presumed to be 50% of its initial price, and the BETs are estimated at 50% of their cost excluding the battery expense, with the battery retaining 15% of its value. For the 15-year span, the residual values for both the vehicle and battery are assumed to be zero. Battery replacements are not considered within the first 5 years but are anticipated after 15 years based on mileage and assumed battery life of 1500 deep discharge cycles, with replacement costs mirroring the original battery specifications.

The expense for the nth year of the battery-electric vehicle life is calculated as follows:

$$(\text{TCO})\text{n} = [(\text{Energy})\text{elec} + (\text{maint.})\text{BET}]/(1+\text{d})\text{n-1} \qquad \text{Eq. 12}$$

$$= [[(\text{kWh/mi}) \text{ x } (\text{OEF}) \text{ x}(\$/\text{kWh})\text{elec}) + (\$/\text{mi})\text{maintBET.}] \text{ x } (\text{miles/yr.})\text{n}]/(1\text{-d})\text{n-1} \qquad \text{Eq. 13}$$

The discounted TCO is then given by the following:

$$(\text{TCO})\text{total} = (\text{Veh cost})\text{BET} + \sum \text{n } (\text{TCO})\text{n} + (\text{Residual- Veh +bat})/\ (1+\text{d})\text{N-1}\text{ , N=nmax} \qquad \text{Eq. 14}$$

$$\text{(TCO/mi)total} = \text{(TCO)total} / \textstyle\sum \text{n (miles/yr)n} \qquad \text{Eq. 15}$$

The corresponding relationships for the baseline diesel vehicle are the following:

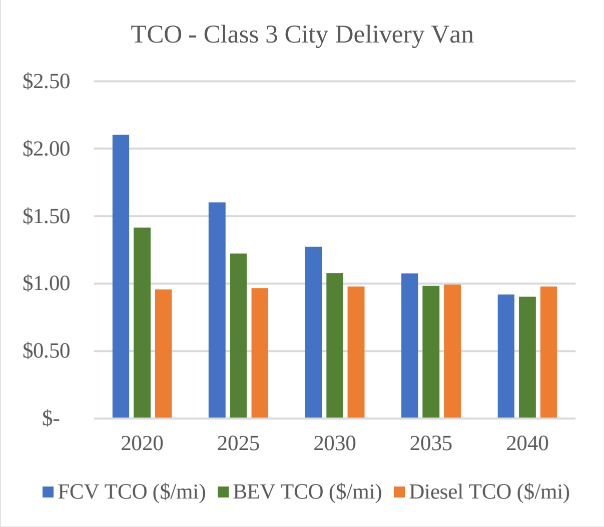
$$\text{(TCO)n} = \text{[[(mi/gal)D x (\$/gal)D} + \text{(\$/mi)maintD.] x (miles/yr.)n]/(1-d)n-1} \qquad \text{Eq. 16}$$

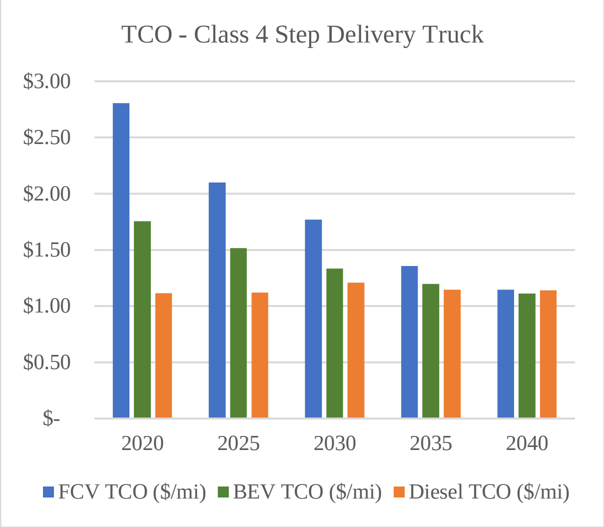
$$\text{(TCO)total} = \text{(Veh cost)Diesel} + \textstyle\sum \text{n (TCO)n} + \text{(Residual- Veh)/ (1+d)N-1 , N=nmax} \qquad \text{Eq. 17}$$

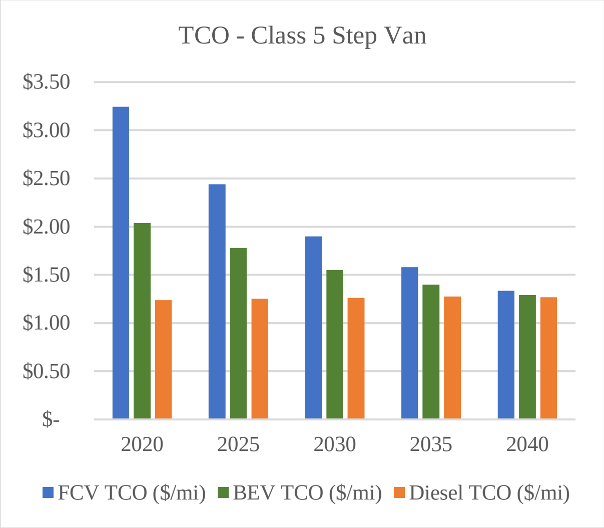
$$\text{(TCO/mi)total} = \text{(TCO)total} / \textstyle\sum \text{n (miles/yr.)n} \qquad \text{Eq. 18}$$

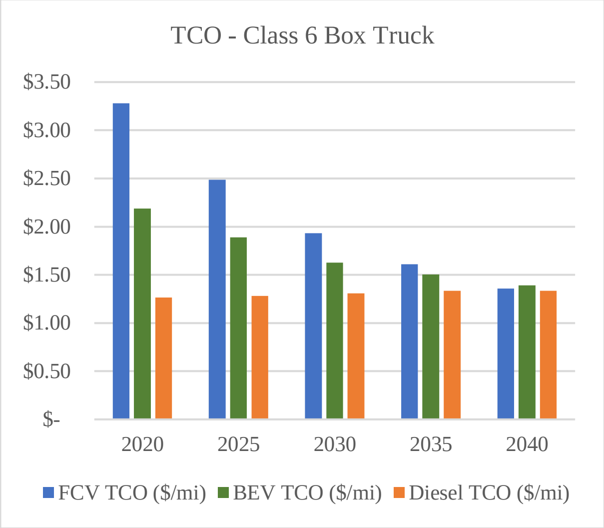
The method for calculating the TCO for BETs is also applicable to FCETs, having been carefully adapted by appropriately designing the input parameters for the functions. The resulting TCOs for BETs and FCETs are illustrated in **Figure 7**. In the MDV market, projections suggest that by 2040, both BETs and FCETs could potentially achieve TCOs comparable to those of diesel trucks. However, in the HDV market, such as for Class 8 long-haul trucks, it remains challenging for both BETs and FCETs to match the TCO of diesel trucks in the coming decade. This is especially true for BETs, whose TCOs are expected to be higher than those of FCETs due to factors such as higher initial costs and battery replacement expenses.

Compared to the ICCT analysis [59] for Class 8 long-haul trucks in 2030, our study shows similar trends in the comparison between FCETs and ICEVs—specifically, the TCO of FCETs will still be significantly higher than that of ICEVs. However, ICCT anticipates that the TCO for BETs will be comparable to their diesel counterparts, attributing this to significantly lower operational expenses, the higher energy efficiency of battery electric powertrains, and reduced maintenance costs. In contrast, our analysis shows that the large battery pack (1000–1500 kWh), which is expected to account for more than 60% of the Class 8 long-haul truck total cost, is priced at \$313/kWh (2020) and \$121/kWh (2040) at the battery system level (including profit markup and cell-to-pack integration factor). Such high battery costs directly result in a much higher initial purchase cost for BETs compared to both FCETs and diesel trucks, even in the long term. Additionally, we find that TCO values are highly sensitive to annual driving range, especially for heavy-duty trucks (some studies assume only 50,000 miles annually, while in our study, we assume 100,000 miles annually). However, the mileage ratio between ZEVs and ICEVs remains almost constant despite variations in annual mileage inputs.


TCO - Class 3 City Delivery Van
$2.50
$2.00
$1.50
$1.00
$0.50
$-
2020
2025
2030
2035
2040
FCV TCO ($/mi)
BEV TCO ($/mi)
Diesel TCO ($/mi)


TCO - Class 4 Step Delivery Truck
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$-
2020
2025
2030
2035
2040
FCV TCO ($/mi)
BEV TCO ($/mi)
Diesel TCO ($/mi)


TCO - Class 5 Step Van
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$-
2020
2025
2030
2035
2040
FCV TCO ($/mi)
BEV TCO ($/mi)
Diesel TCO ($/mi)


TCO - Class 6 Box Truck
$3.50
$3.00
$2.50
$2.00
$1.50
$1.00
$0.50
$-
2020
2025
2030
2035
2040
FCV TCO ($/mi)
BEV TCO ($/mi)
Diesel TCO ($/mi)

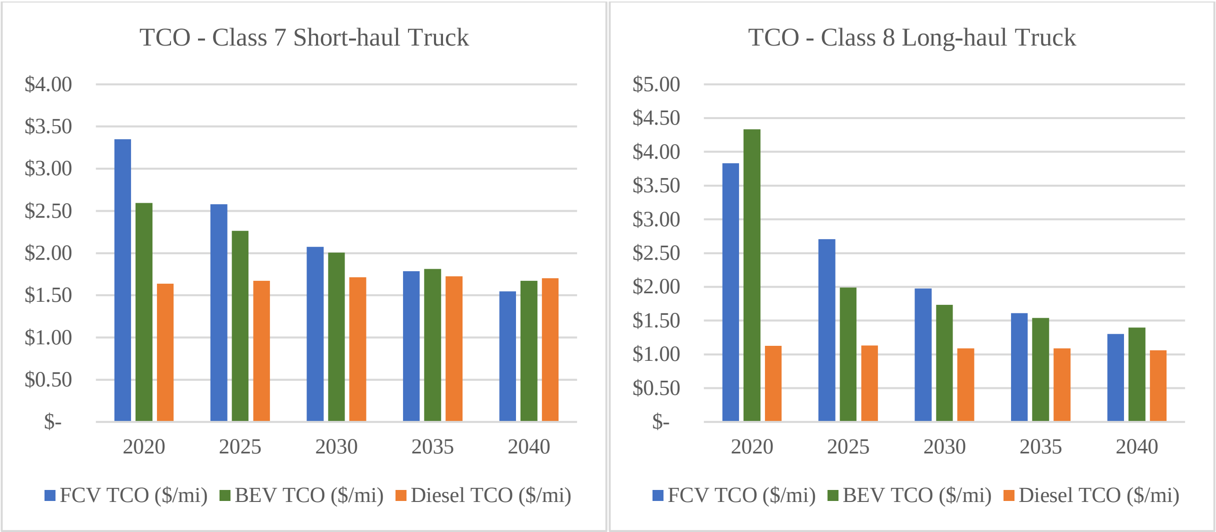


Figure 7. TCO of BETs and FCETs from class 3 to class 8.

6 ZEV infrastructure technology and cost

The H2 refueling infrastructure must be available for the FCETs before sales can be expected. Trucks used in regional applications can return to a private terminal every night, which can be built and operated by the fleet owner. This terminal can be appropriately sized to for the fleet that uses it, thus its utilization factor will be known. Long-haul trucks that drive long distances (500 miles) every day will have to be refueled at public stations located along or near highways traveled by those trucks. These refueling stations must be built over wide areas of California and nearby states before sales of long-haul FCETs can be expected. The utilization factors for these stations will be low and uncertain, making profitable operation of them very difficult. The public hydrogen stations will likely require subsidies from the California and federal governments, while the number of FC vehicles on the road increases. The cost of providing the infrastructure for both H2 FC and BETs in private terminals and public stations has been studied. The cost of the two types refueling facilities will be discussed separately.

6.1 Private terminals for refueling H2 FC and battery-electric regional trucks

The management of terminals to refuel FCETs will be similar to refueling trucks operating on compressed and liquefied natural gas (NG). NG refueling is done in private or public stations using fast-fill or fill-time approaches. Public NG stations use the fast-fill approach and private refueling facilities often use the fill-time approach to reduce the cost of constructing the station. In this study of private terminals for hydrogen refueling over-night, we used the fill-time approach.

The configuration of the private H2 refueling station will be similar to the fast-fill public station shown in **Figure 8**. However, the components in the station will be selected to accommodate slower fill-time (FT) operation. The key inputs for the calculation of the slow-fill hydrogen facility are the kg H2 to be filled (W_{H2}), maximum refill time (FT in minutes), and the period available for refueling (t_{fl} in hours). The hydrogen would be delivered to the station by truck and stored in tube-trailers. The maximum refueling rate (kgH2/min) is given by

$$(\mathrm{kgH2/min})_{max} = (W_{H2}/FT)*ovdsf$$, where ovdsf is the system over-design factor. Eq. 19

The maximum number of FCETs that can be refueled per dispenser is

$$VH_{mx} = t_{fl}*60*ovdsf/FT$$ Eq. 20

The maximum H2 needed per day is

$$(\mathrm{kgH2/da})_{max} = VH_{mx}*W_{H2}$$ Eq. 21

The unit component costs used in the calculations were those assumed in the Hydrogen Delivery, Storage, and Dispensing Analysis Model (HDRSAM) for the low component cost option (high production of components). Cost calculations were made for city delivery and short haul Class 8 trucks for FT values of 60, 45, and 30 minutes, a refueling period of 15 hours, and a system over-design factor of 1.3. The calculation procedure for a typical case is shown in **Table 18**.

Table 18. Calculation procedure for a H2 refueling terminal.

700 bar H2 terminal		H2 stored in tube-trailer	
maxtrucks designper day	35	Max hours of refueling	13.4
AvkgH2 per vehicle kg	35	kgH2 in HP storage	70
Av refueling time minutes	23	cost of HP storage $/kgH2	1000
refueling rate kgH2/min	1.5	Cost of HP storage $	70,000
refueling operation hours/da	13.4	Max kg thru compressor/da	910
kgH2/day	1225	refueling H2 needed kg	1225
Hrs refueling/day	13.5	system oversized factor	-0.25
minimum number of hoses	1	HP compressor power kW/kg/h	1
Overhose factor	1	HP compressor power kW	91
needed number of hoses	1	Cost HP compressor $/kW	2700

Calculation of refueling rate		Cost of HP compressor $	245,700
maxtrucks per da	40	Kg/hr of compressor	91
Avg kg fill	35	cost of refrigeration $/kg/h	500
Maxfill minutes	30	cost of refrigeration $	45,500
refuelingrate kg/min	1.16	number dispenser needed	1
trucks rfillhr	20	Cost per hose unit $/unit	40,000
Max refueling rate kg/min	1.5	cost of H2 dispensers $	40,000
		cost of hardware $	401,200
		Installation cost $	200,600
		Total terminal cost $	851,800
		site preparation & engineering	250,000
		Total Station invest. cost $	851,800
		$/kgH2/da	695.3469
		$/veh	24,337
		$/kg	0.190506

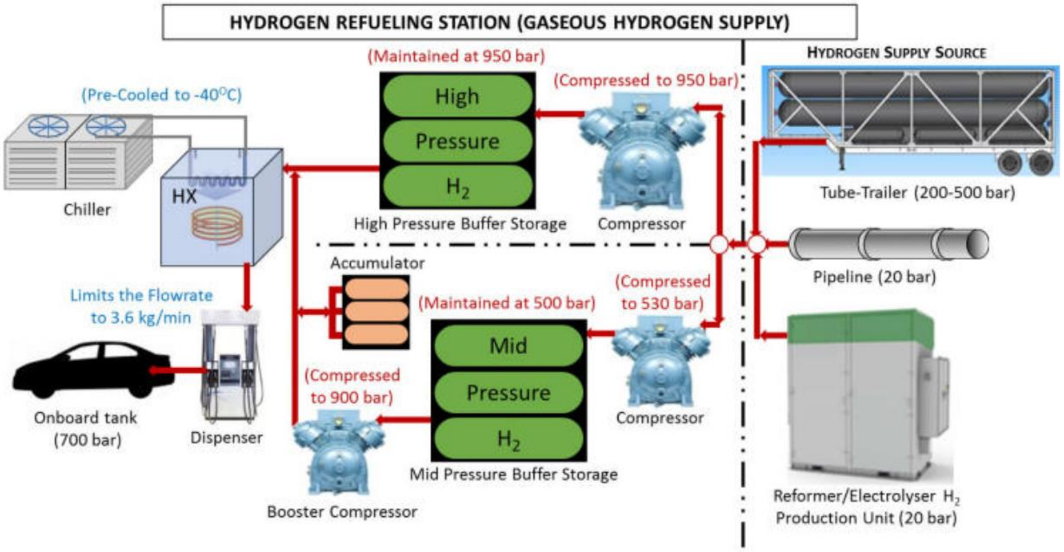


Figure 8. Schematic for a H2 fueling station [60].

Cost calculations were made for city delivery and short-haul Class 8 trucks for FT values of 60, 45, and 30 minutes, a refueling period of 12 hours, and a system over-design factor of 1.3. The results are shown in **Table 19**. The costs of the stations are dependent on the fill time and the number of dispensers needed. The k$/vehicle of the station decrease continuously as the size of the station is increased.

Table 19. Projected costs of slow-fill H2 refueling stations for fleets of trucks.

Vehicle type	Number of hoses	Max fill time minutes*	Maximum No. of vehicles	Station cost k$	Station cost effect on $/kgH2 dispensed	k$/vehicle refueled
City delivery	1	60	18	391	0.78	22
8 kg refills		45	24	384	0.64	19
		30	36	421	0.47	13
	2	60	36	550	0.52	15
		30	72	663	0.32	9
	3	60	54	669	0.42	12
		45	72	726	0.35	10
		30	108	839	0.27	8
Short haul	1	60	18	551	0.45	31
18.8 kg refills		45	24	602	0.37	25
		30	36	701	0.28	19
	2	60	36	744	0.30	21
		30	72	1018	0.21	14
	3	60	54	935	0.25	17
		45	72	1069	0.22	15
		30	108	1335	0.18	12

*12 hr fill period, station over-design factor of 1.5

Calculations were also made using HDRSAM for fast-fill public hydrogen refueling stations. The results are shown in **Table 20**. Comparing the cost results in **Table 19** and **Table 20** shows the cost advantage of the slow-fill approach for refueling fleets for which the refueling can be scheduled ahead of time.

Table 20. Fast-fill station costs calculated using HDRSAM.

Vehicle type	Number of vehicles	Station cost k$	k$/vehicle

City delivery	16	815	51
8 kgH2 refill	20	837	42
	30	890	30
Short haul Class 8	16	1345	84
18.8 kgH2 refill	20	1480	74
	30	1667	56

We developed an Excel spreadsheet model to calculate the cost of the facility needed to charge the truck batteries using chargers of different power (kW). For battery charging at terminals, we assumed a charging time of 2 to 3 hrs. The model includes a detailed description of the battery in terms of voltage, ampere-hour (Ah), and the fleet size. The charger costs are based on information from Tritium [61] and Asea Brown Boveri (ABB) [62] via costs of constructing a battery charger facility on the UCD campus to recharge Unitrans New Flyer electric buses . Cost information was available for chargers up to 350 kW. The charger costs in this study were calculated from the relationship below

$$\$/\text{kW} = 1175 - 1.55\ \text{Pch} - 0.000417\ P_{ch}^2, \qquad \text{Eq. } 22$$

which indicates that the unit cost ($/kW) including installation decreases as the power P_{ch} of the charger increases. Each charger can have two charging ports if the charger power permits. The model outputs show the charger power resulting in the minimum cost for the vehicles and fleets being analyzed. This charger cost does not include any cost of upgrading the maximum power available to the charger facility and cost savings when many chargers are installed at one time. These costs are both uncertain and dependent on the particular project.

Typical results using the station cost model are shown in the following tables. The results are given for charging times of 2 and 3 hours, and in terms of the station cost and the cost per vehicle that can be charged at the station. The charging times are for charging the batteries to 95% of the rated Ah capacity of the cells. If maximum vehicle range is needed, the batteries could be charged to 100% of the cell capacity by increasing the charging time to 3 and 4 hours rather than 2 and 3 hours.

Table 21 and **Table 22** show results for stations for city delivery and Class 8 short haul trucks. The costs are higher for 3hr than 2hr battery charging stations, but are independent of fleet size when normalized by cost per vehicle. The results in **Table 21** show the station cost for different capacity stations and the incremental cost of enlarging a charging station as the electric truck fleet is increased in size. The results indicate that the enlarging process should be manageable at a reasonable cost. It can be expected that charging the batteries in 3 hrs will increase the cycle life of the batteries. When maximum vehicle range is not needed, cycle life can also be increased by altering the charging protocol by reducing cell $V_{cut\text{-}off}$ (maximum battery voltage) for the charge. **Table 22** shows the costs of the minimum size stations that can be established to meet vehicle battery requirements and charger power used in the stations. Even for the small stations, the effect on the cost of the dispensed electricity for charging is relatively small.

Table 21. Battery charging station costs for various size stations.

Vehicle class	Number of vehicles	2 hr charging Station cost k$	k$/ veh	Station cost on electricity dispensed $/kWh	3 hr charging Station cost k$	k$/veh	Station cost on electricity dispensed $/kWh
Class 3 City delivery		150 kW chgr 142 kWh bat			150 kW chgr 142 kWh bat		
	8	140	17.5	0.041	203	25.4	0.06
	16	280	17.5	0.041	406	25.4	0.06
	24	420	17.5	0.041	609	25.4	0.06
	40	700	17.5	0.041	1015	25.4	0.06
	80	1400	17.5	0.041	2031	25.4	0.06
Class 8 Short haul		250 kW chgr 378 kWh bat					
	8	381	47.6	0.042	407	50.9	0.045
	16	761	47.6	0.042	814	50.9	0.045
	24	952	39.7	0.035	1220	50.9	0.045
	40	1713	42.8	0.038	2035	50.9	0.045
	80	3236	40.5	0.03	4070	50.9	0.045

Table 22. Station costs for a minimum size charging station.

Vehicle class	Charging	kWh	Number of vehicles	Charger K$	k$/vehicle	Station cost on electricity dispensed $/kWh
Class4 City delivery	100 kW 2 hr	142	5	102	20.4	0.048
Class 8 short haul	250 kW 2 hr	378	6	190	31.6	0.028

In this section, we analyze the costs of providing battery charging and H2 refueling facilities for fleets of trucks at over-night terminals. The comparisons are made in terms of the k$/truck when the full capacity of the facility is utilized. The cost results are dependent on the refilling time for both battery-electric and hydrogen FCETs. In general, the costs per vehicle are lower for shorter refueling times. The results indicate that refilling considerations favor BETs for smaller trucks and hydrogen FCETs for larger trucks.

6.2 Public refueling stations for Class 8 long haul fuel cell electric trucks

We developed a spreadsheet model of the economics of building stations from 2024-2040, which allows for over-building stations in the early years. The model permits the determination of the H2 refueling station characteristics (number, kgH2/da, number of dispensers per station, cost) including Low Carbon Fuel Standard (LCFS) credits and subsidies to defray the cost of the stations as the infrastructure grows. The number of vehicles in the FCET fleet in 2024-2040 and the number of stations available each year and their capacity (kgH2/da) and construction cost ($/kgH2/day) are inputs to the spreadsheet. Results for Class 8 FCETs are shown in **Table** 23 – **Table 25**. As expected, the utilization of the refueling stations is low before 2028 and approaches 0.7 by 2040. The results also indicate that stations will require either LCFS credits or a subsidy to achieve profitability for the first 5 years of operation. The projected total investment in 2040 in the H2 refueling stations is projected to be $2.9 billion for 700 -bar, CH2 stations and $1.1 billion for LH2 stations using a cryogenic pump for compression of the H2.**Table** 23Table 23. H2 refueling station (CH2 and LH2) costs for Class 8 FC trucks- fast growth of sales.

Yr	Fleet No. of vehicles	No. of stations	Utilization	kgH2/day	CH2 cost Station M$	Cumulative Cost Station M$	CH2 $/veh k$	LH2 Cost Station M$	Cumulative Cost Station M$	LH2 $/veh k$
2024	200	20	0.16	2000	6.1	122	610	1.7	34	171
2026	2000	30	0.43	2500	6.9	187	187	2.1	54	55
2028	3000	75	0.42	3000	7.3	507	169	2.4	162	54
2030	6100	120	0.46	3500	7.2	833	136	2.6	280	46
2032	13,000	190	0.54	4000	7.6	1350	104	2.9	481	37
2035	20,000	240	0.65	4000	7.2	1720	86	2.8	619	31
2038	35,000	360	0.67	4500	7.4	2590	73	3.0	980	28
2040	47,000	415	0.77	4500	6.9	2990	64	2.9	1140	24

Table 24. H2 refueling station (CH2 and LH2) costs for Class 8 FC trucks-slow growth of sales.

Yr	Fleet No. of vehicles	No. of stations	Utilization	kgH2/day	CH2 cost Station M$	Cumulative Cost Station M$	CH2 $/veh k$	LH2 Cost Station M$	Cumulative Cost Station M$	LH2 $/veh k$
2024	100	21	0.08	2000	6.1	131	1310	1.7	36	365
2026	400	30	0.22	2000	5.5	182	455	1.6	52	130
2028	1600	51	0.35	3000	7.3	330	206	2.4	101	63
2030	3050	60	0.42	4000	8.2	408	134	3.0	121	42
2032	6000	76	0.52	5000	9.5	556	92	3.6	184	30
2035	9455	88	0.58	6000	10.7	690	73	4.1	236	25
2038	14,000	117	0.64	6000	9.8	974	70	4.0	352	17
2040	20,000	151	0.70	6000	9.2	1290	64	3.8	483	24

Table 25. LCFS credits for H2 refueling stations for fleets of class 8 FC trucks.

Yr	Fleet No. of vehicles	No. of. Sta.	CH2 Cost Sta k$	Cumulative Cost Sta. M$	Sta. LCFS Credt $M	Cumulative LCFS Credt $M	CH2 $/Veh k$
2024	100	21	6.1	131	2.2	47	1310
2026	400	30	5.5	182	2.3	68	455
2028	1600	51	7.3	330	2.9	121	206
2030	3050	60	8.2	408	3.2	149	134
2032	6000	76	9.5	556	3.4	202	92
2035	9455	88	10.7	690	3.2	244	73
2038	1400	117	9.8	974	2.4	325	70
2040	20,000	151	9.2	1290	1.6	392	64

6.3 Public battery charging stations for Class 8 long haul electric trucks

A spreadsheet model was also prepared to calculate the cost of charging batteries of class 8, long haul BETs [63]. The fleets of BETs for 2024-2040 analyzed were fairly large reaching 43,000 trucks in 2040. The range of the BETS was 350 miles requiring about 700 kWh of charge at each charging. The batteries were recharged in one hour (60 minutes) requiring a 700 kW charger that cost $702,000, resulting in the need for 1.4 MW at each 2 charger station. The charger cost included its installation and any site upgrade (transformer), but not any cost to the electric utilities of supplying the 1.4 MW to the stations. The results of the spreadsheet calculations for the battery-charging infrastructure are shown in **Table 26**. A total of 3800 chargers and 1900 stations are projected to be needed by 2040, at an accumulated cost of about $960 million for a fleet of 43,000 Class 8 long-haul trucks in California. The cost ($/veh) for BET is much lower than for H2 refueling stations storing and dispensing CH2, but only slightly lower than H2 stations storing and dispensing LH2. The added cost on the electricity of the station construction decreases from 11 cents/kWh in 2024 to less than 1 cent/kWh in 2040.

The stations are projected to be profitable including LCFS credits, but not profitable without them. BETs have larger energy efficiency ratio (EER) than FCET. The BETs have EER values of 4-5, compared to 1.5-2 for FCETs, resulting in considerably larger LCFS credits for BETs than for FCETs.

Table 26. Projected infrastructure costs for public battery charging in Class 8 LH BETs.

Yr	Fleet No. of vehicles	No. of. chargers	Utiliz.	Charger Cost k$	Accum Charger cost M$	Charger k$/veh	LCFS Credits k$/chgr	Accum. LCFS Credit M$
2024	600	330	0.09	702	233	388	386	64
2026	2400	498	0.23	702	465	194	655	119
2028	4200	552	0.36	702	583	138	852	141
2030	9000	1000	0.42	702	619	69	842	330
2032	16,000	1442	0.52	702	934	58	829	514
2035	23,000	1856	58	702	1240	54	683	655
2038	33,000	2406	0.64	702	1540	47	506	794
2040	43,000	2852	0.71	702	1920	45	340	870

6.4 General considerations for providing infrastructure for zero-emission MD/HD trucks

In this section, the infrastructure needed to operate fleets of H2 FC and battery-electric MDHD trucks is summarized to determine the detailed design and cost of the stations needed for fleets of various sizes. The analysis was done for private terminals for over-night refueling and for public stations along arterials and busy highways. It was assumed that most trucks operated in cities and surrounding areas would use private terminals and long-haul freight trucks would use public stations. Hence Class 3-6 MD trucks would use primarily private terminals for overnight H2 refueling and battery charging and Class 8 long-haul trucks would use primarily the public stations along highways. MD trucks could use public stations being built for LD ZEV vehicles for opportunity refueling when needed. The public refueling stations for HD vehicles along highways could be built to accommodate both HD and LD vehicles.

The refueling station analyses were done using Excel spreadsheet models with components sized to handle the refueling events in terms of energy transfer rates and refueling times. For MDHD FCETs, the refueling time at public stations was assumed to be 5-10 minutes and at private terminals 30–60 minutes. Refueling Class 8 trucks requiring 40–60 kgH2 in 10–15 minutes should not present a problem. Battery charging times at private terminals were taken to be 1–2 hours and at public chargers 20–60 minutes. For large batteries (>300 kWh), at the present time it will be necessary to charge the batteries with multiple chargers and a segmented battery pack for short charging times because chargers currently available on the market are limited to about 500 kW. High voltage battery packs and higher power chargers are being developed to facilitate fast charging of large battery packs for trucks.

Calculating the cost of H2 refueling and battery charging is rather straightforward, but at present there is considerable uncertainty in the cost of the components and the cost to install them at a new station. The cost of an H2 refueling stations is often expressed in terms of $/kgH2/day capacity. The present H2 station unit cost is $3000–4000/kgH2/day. We assumed in the present calculations that the cost will decrease to $1500–2000 /kgH2/day by 2040. The cost of a battery charging station will depend on the power kW of the charger needed. Charger costs are often given as $/kW. At present, charger costs can vary over a wide range of $200-1000/kW, depending on the power of the charger and the manufacturer. In our cost study, we assumed high power chargers cost $300-500/kW uninstalled. Estimating installation and grid connection costs is uncertain, but it can be equal to the cost of the charger.

The cost of refueling infrastructure depends on the number of vehicles in the fleet and how fast the vehicles are refueled. Hence it is convenient to express the station cost in terms of the $/veh in the fleet to be refueled. The $/veh values are much higher for refueling class 8 trucks than smaller class 3-4 trucks, primarily due to the difference in the volume/weight/kWh of the electricity or H2 transferred to the vehicles. The results of the infrastructure cost calculations are summarized in **Table 27** and **Table 28**. The cost of refueling vehicles at the private terminals is much less than at public stations because the terminals have a high utilization factor by design and over-night refueling can be done over a longer time. In the private terminals, the cost of battery-charging is considerably less than the cost of refueling H2 FCET. The cost of providing the infrastructure for battery charging at public stations for Class 8 long-haul trucks is less than for hydrogen refueling, but the refueling time is much shorter for FCETs than BETs.

Table 27. Summary of costs for private terminals in California.

Vehicle type	Number of vehicles	Charging or refueling time (hr)	Terminal cost (k$)	k$/vehicle	Station energy cost ($/kWh or $/kgH2)
Battery Electric					
City delivery					
	8	2	140	18	0.04
	16	2	280	18	0.04
	40	2	700	18	0.04
Short haul class 7					
	10	2	381	38	0.03
	16	2	761	48	0.04
	30	2	1142	38	0.03
	62	2	2475	40	0.04
Hydrogen					
City delivery					
	36	0.5	421	13	0.47
	72	0.5	663	9	0.32
	108	0.5	839	8	0.27
Short haul class 7					
	36	0.5	701	19	0.28
	72	0.5	1018	14	0.27
	108	0.5	1335	12	0.18

Table 28. Summary of costs for public battery-charging and H2 refueling stations in California for class 8 long-haul trucks.

Fleet	Number of chargers or H2 stations	Accum charger or H2 station cost M$	k$/veh	Station $/kWh or $/kgH2
Battery charging (1 hr)				
600	274	192	320	0.11
2400	802	467	235	0.08
9000	1467	566	52	0.02
23,000	2438	682	30	0.01
43,000	3806	960	22	0.008
Hydrogen refueling (5-10 minutes)				
400	30	178	444	3.00
1600	75	400	250	1.70
3050	120	587	192	1.20
6000	190	859	143	0.92
9450	265	1140	120	0.78
14,000	350	1420	101	0.64
20,000	450	1750	87	0.56

7 ZEV choice modeling and PPA results

In addressing the need to reduce the carbon footprint of transportation, the state of California has pioneered the adoption of ZEVs, including BETs and FCETs, in the MD/HDV segments. These efforts aligne with legislative mandates that target a complete transition to ZEVs by 2040. We developed a discrete choice model to analyze vehicle choices within the MD/HDV market, incorporating seventeen decision factors (**Table 29**). This model [64] offers insights into the probability of ZEV adoption over conventional ICEVs, considering variables such as vehicle cost, driving range, model availability, refueling or charging inconvenience, and TCO. The findings indicate that California's ZEV market share targets can be achieved through diversified strategies that enhance vehicle affordability, expand model selection, and improve refueling and charging infrastructure. For MD/HDVs, the transition to ZEVs is further facilitated by financial incentives and policy measures that support the adoption of cleaner vehicle technologies. In this section, we focus on the market penetration of each market segment for MD/HDVs under various development scenarios (see **Table 30**) with a focus on different charging and hydrogen refueling infrastructure and incentives.

Table 29. Decision factors for the purchase of vehicles using various technology options.

No.	Attribute
1	Vehicle cost
2	All-electric or hydrogen driving range (mi)
3	Number of models available to purchase
4	Inconvenience to charge or refuel ZEVs compared to ICEVs in the city
5	Inconvenience to charge or refuel ZEVs compared to ICEVs on the highway
6	Battery charging or hydrogen refueling time (minutes)
7	Availability of a second market for ZEVs compared to ICEVs
8	Maintenance cost ($/mi)
9	Energy operating cost ($/mi)
10	Environmental concern compared to ICEVs
11	Safety concerns for ZEVs compared to ICEVs
12	Drivability of ZEVs compared to ICEVs
13	Reliability/durability of ZEVs compared to ICEVs
14	TCO ($/mi)
15	Cost of a terminal ($/vehicle) to provide for charging/hydrogen refueling compared to ICEVs
16	Payload penalty reduction compared to ICEVs

Table 30. Vehicle penetration scenarios under different assumptions for MD/HDVs.

Model	Code	Chargers+/inconvenience	H2 stations+/inconvenience	Incentives
S1	S121	Base terminal cost for class 3 to class 7, base charger availability for class 8	Base terminal cost for class 3 to class 7, base H2 availability for class 8	With plan 1[a]
	S122	Base terminal cost for class 3 to class 7, base charger availability for class 8	Base terminal cost for class 3 to class 7, base H2 availability for class 8	With plan 2[b]
	S123	Base terminal cost for class 3 to class 7, base charger availability for class 8	Base terminal cost for class 3 to class 7, base H2 availability for class 8	With plan 3[c]
	S124	Base terminal cost for class 3 to class 7, base charger availability for class 8	Base terminal cost for class 3 to class 7, base H2 availability for class 8	Without
S2	S221	Reduced terminal cost for class 3 to class 7, improved charger availability for class 8	Base terminal cost for class 3 to class 7, base H2 availability for class 8	With plan 1[a]
S3	S321	Base terminal cost for class 3 to class 7, base charger availability for class 8	Reduced terminal cost for class 3 to class 7, improved H2 availability for class 8	With plan 1[a]
S4	S421	Reduced terminal cost for class 3 to class 7, improved charger availability for class 8	Reduced terminal cost for class 3 to class 7, improved H2 availability for class 8	With plan 1[a]
	S423	Reduced terminal cost for class 3 to class 7, improved charger availability for class 8	Reduced terminal cost for class 3 to class 7, improved H2 availability for class 8	With plan 3[c]
	S424	Reduced terminal cost for class 3 to class 7, improved charger availability for class 8	Reduced terminal cost for class 3 to class 7, improved H2 availability for class 8	Without

[a] Incentives and rebates including IRS-Clean Vehicle Tax Credit (CVTC) [65] and California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) [66] and between 2020 and 2030, but with a steady decrease rate from 2024 forward.

[b] Both HVIP and CVTC are available between 2020 and 2036, but with a steady decrease rate from 2024 forward.

[c] Both HVIP and CVTC are available between 2020 and 2040, selecting the larger of the maximum available incentives and the gap between ZEVs and ICEVs.

7.1 The effect of incentives on the FCET

In examining the impact of various incentives on the market penetration of FCET, the study delineates three distinct incentive plans, as illustrated in **Figure 9**. Each incentive plan is represented by a set of bar graphs, showcasing the financial incentives proposed for different classes of MHDVs over a span of two decades, from 2020 to 2040. The key features of each incentive plan are the monetary amount of incentive and the relative treatment of BETs and FCETs and the year when the incentive is terminated. Differences in the three cases are evident in **Figure 9**, which show the monetary amounts of the incentives.

a. Incentive Plan Case 1 visualizes a scenario where a steady distribution of incentives is observed for both BETs and FCETs of classes 3 to 7, with BETs and FCETs being treated equally. The incentives for class 8 trucks are much larger than for the other classes, and the incentives for FCETs are larger than for BETs. Financial incentives and rebates such as the CVTC and California's HVIP are available to support the adoption of cleaner vehicles from 2020 to 2030. However, we assume the amount of these incentives decreases gradually starting in 2024. This phased reduction is designed to transition from direct financial support to market-driven adoption of ZEVs over time.
b. Incentive Plan Case 2 is much like Case 1, except that after 2024 the amount of the incentives is larger than in Case 1, and the incentives do not terminate until 2036. This structured reduction aims to sustain long-term adoption while gradually shifting towards a market-dependent approach. As in Case 1, Class 8 FCETs receive the largest incentive.
c. Case 3 depicts a scenario in which the current incentives will continue without any reductions until 2040 but will not fully bridge the cost gap between ZETs and ICETs. The current procurement incentives (CVTC and HVIP) remain at the same levels, except for Class 8 heavy-duty trucks, where HVIP doubles the incentives for FCETs over BETs. As shown in **Figure 9**, the total procurement incentives cannot cover the cost gap between ZEVs (FCETs and BETs) and diesel trucks before 2026. In the long run, these incentives can cover the gap between FCETs and ICETs across all truck segments (from Class 3 to Class 8) due to the significant reduction in the upfront cost of FCETs. However, for Class 8 heavy-duty long-haul trucks, the incentives cannot cover the gap between BETs and ICETs, as the high initial cost of BETs, driven by the large battery systems, remains even in 2040.

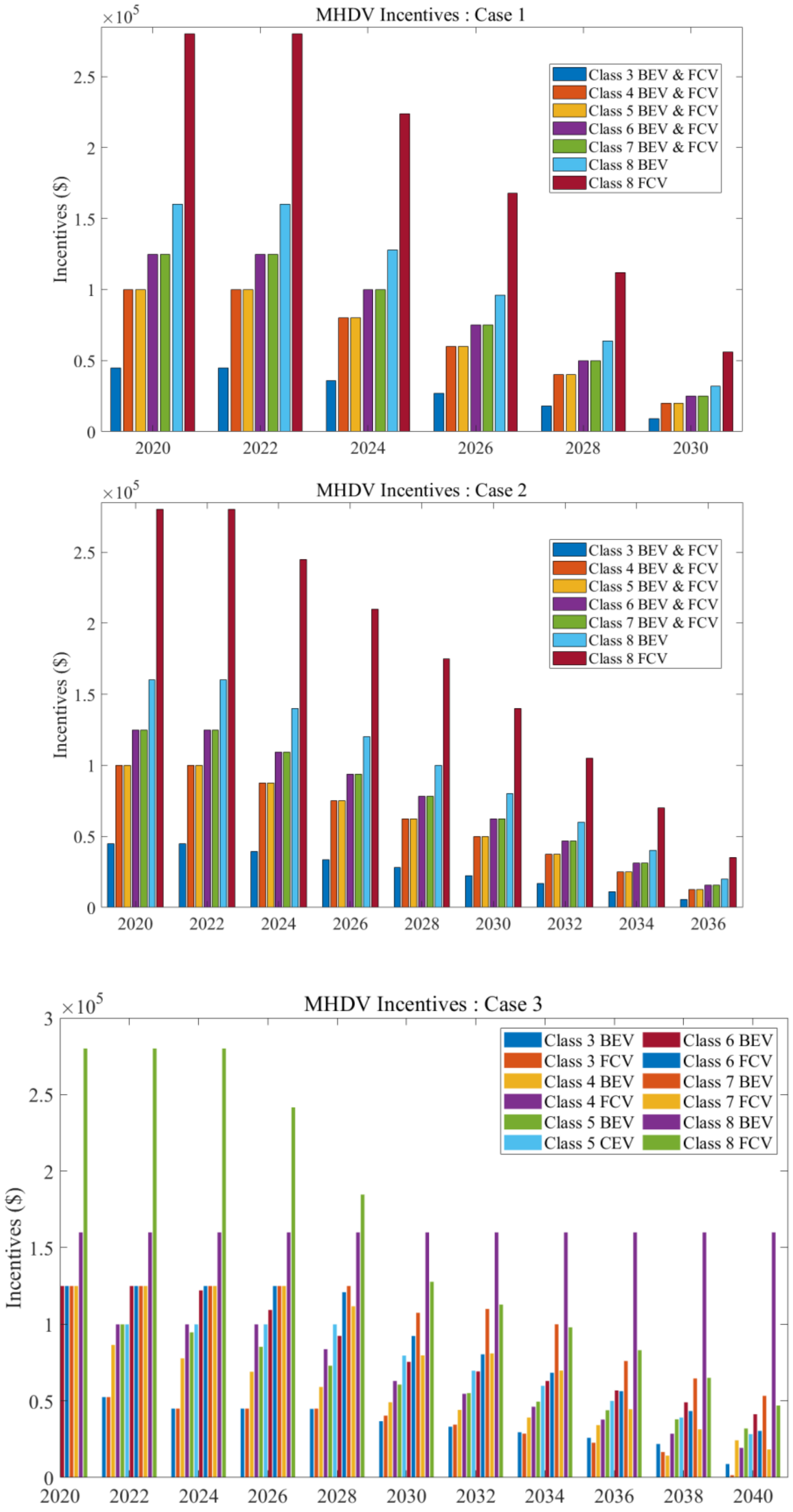
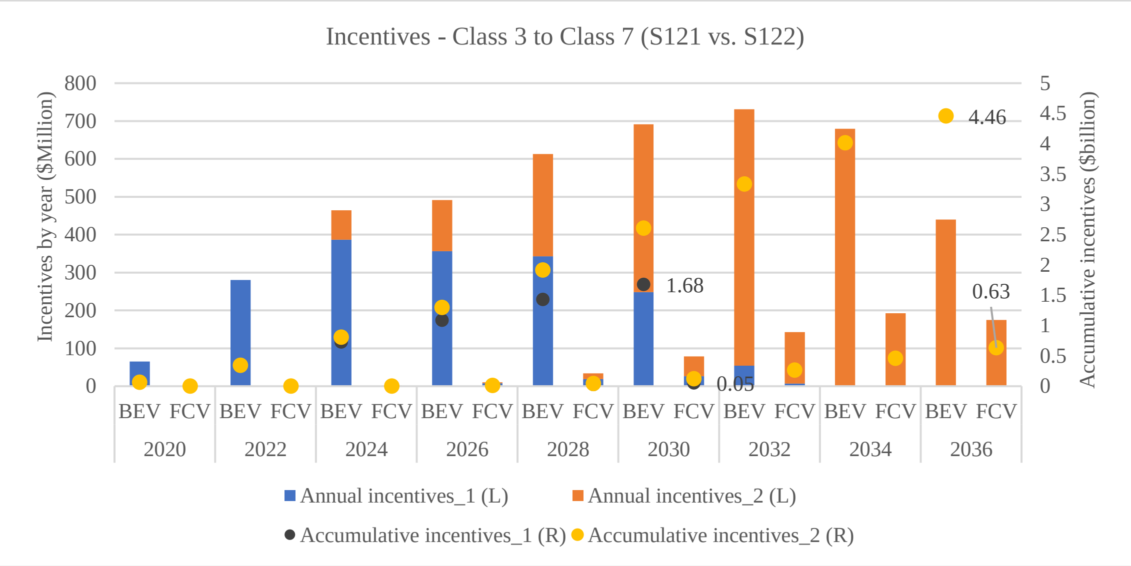


Figure 9. The three incentive plans for analyzing FCET market share impact.

The incentive schedules have been combined with the market shares calculated with the vehicle choice model to determine the annual allocations of incentives expressed in millions of dollars aimed at encouraging the adoption of BETs and FCETs. The calculations were done separately for class 3-7 and class 8 trucks. The results are shown in **Figure 10** for incentive cases 1 and 2. Under the "Incentives_1," by 2030, investment will reach approximately $1.68 billion for BETs and $50 million for FCETs in the category of Class 3-7; it will reach approximately $140 million for BETs and $70 million for FCETs for the category of Class 8. The "Incentives_2" approach projects a more aggressive investment strategy with an estimated total of about $4.46 billion for support of BET sales and $630 million directed towards FCET sales by 2036 in the category of Class 3-7 and about $530 million for support of BET sales and $660 million for Class 8 FCET sales. These projections underscore the importance of the procurement incentives in supporting ZEV sales from 2020-2036.



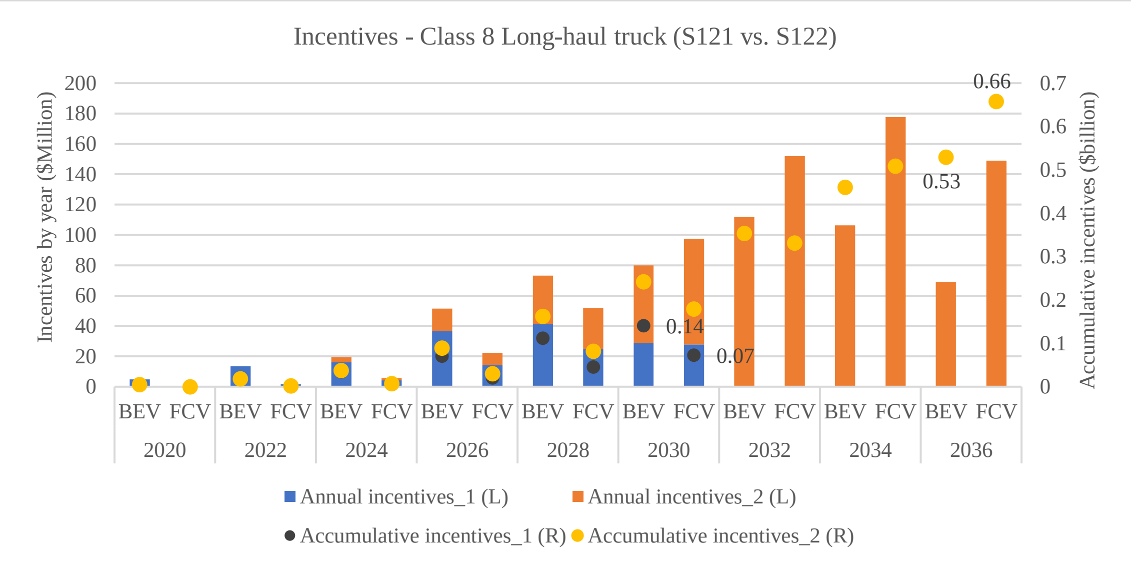


Figure 10. Annual and cumulative incentives under different incentive plans.

Figure 11 provides a comparison of vehicle sales under different incentive scenarios in the market segment of class 3-7 FCETs. Results show that for the "Incentives_2" schedule, cumulative sales are about 39,000 units by 2036, slightly higher than 34,000 units sold under the "Incentives_1" framework. Without the impetus of incentives, FCET sales exhibit a slight decline to 33,000 units. This data suggests that FCET market penetration is positively correlated with the presence of incentives, but the degree of impact is much less than for BETs. In the market segment of class 8 FCETs under the "Incentives_2" schedule, the results show cumulative sales of about 8,000 units by 2036 which was slightly higher than the 7,000 units sold under the "Incentives_1" framework.

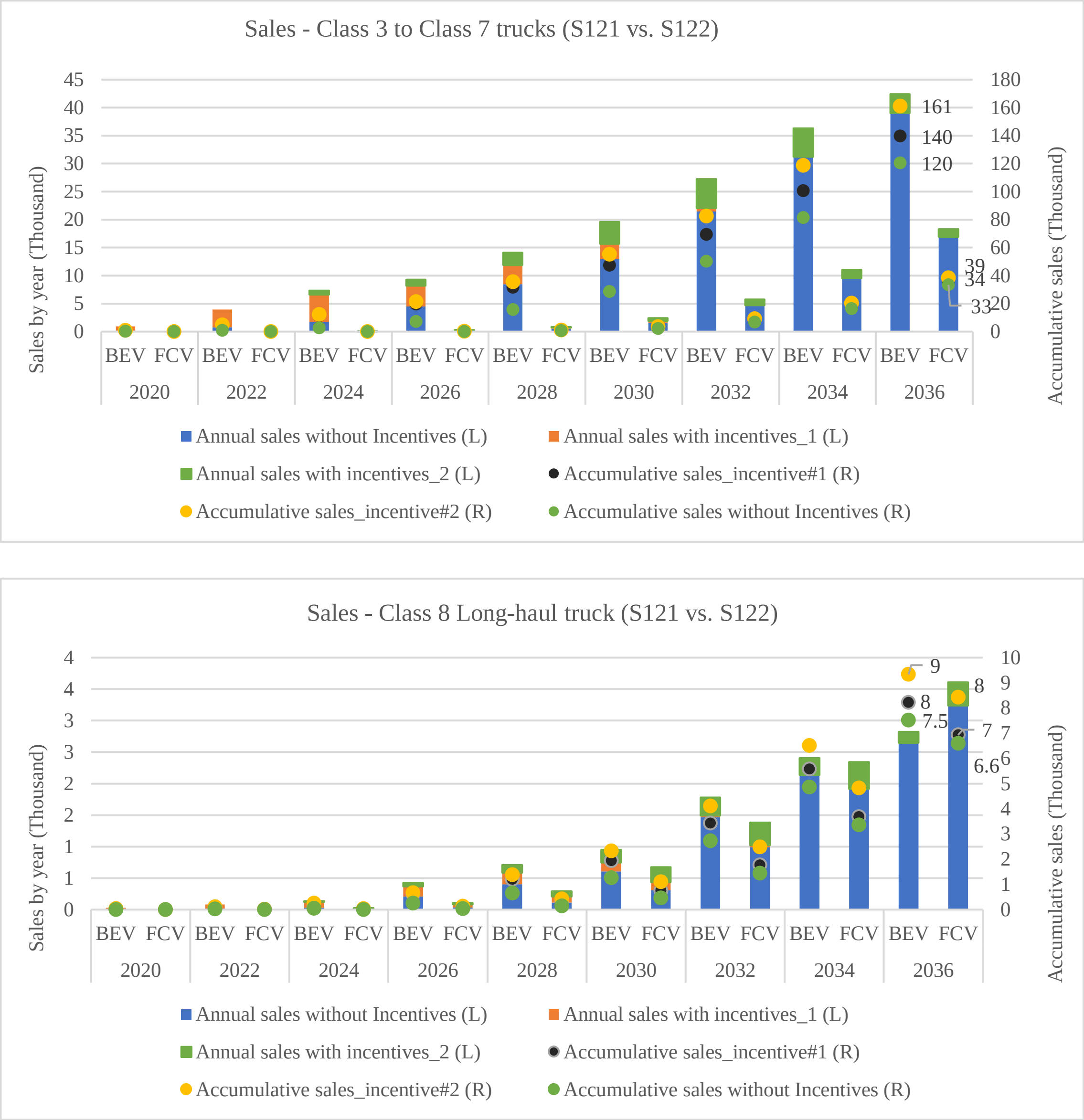
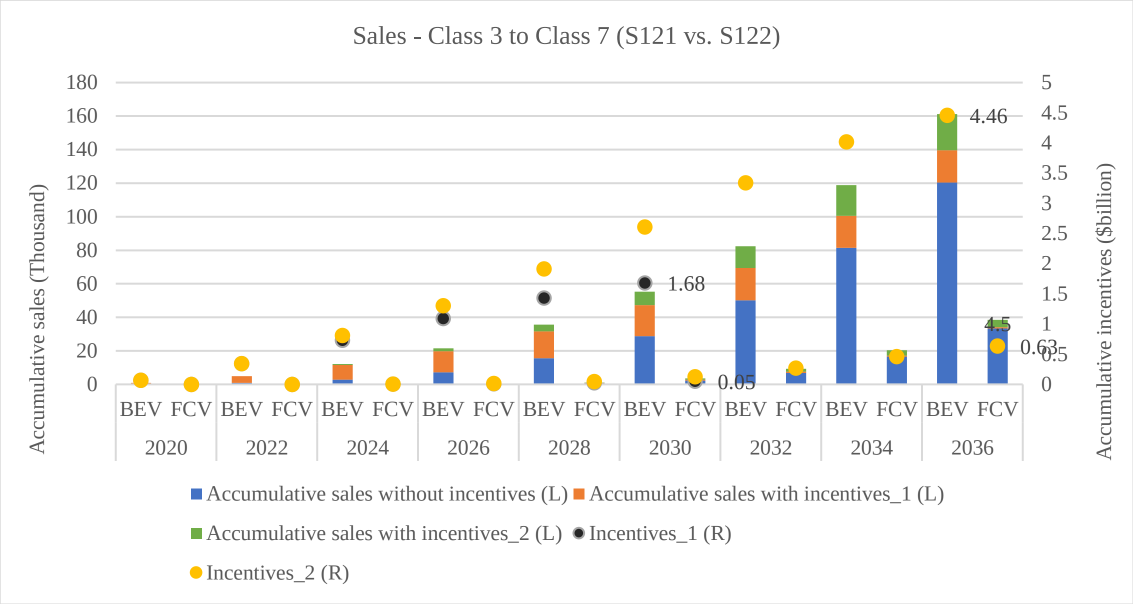


Figure 11. Sales by year and accumulative sales under different incentive plans.

Figure 12 presents the correlation between the cumulative sales of ZEVs and the total incentives provided under two distinct incentive plans. It reveals that in the years between 2030 and 2036 for the class 3-7 truck market, an additional incentive allocation of $580 million would result in an increase of 4,500 units in the accumulated sales of FCETs; for class 8 truck market, an additional incentive allocation of $590 million would result in an increase of about 2,000 units in the accumulated sales of FCETs.



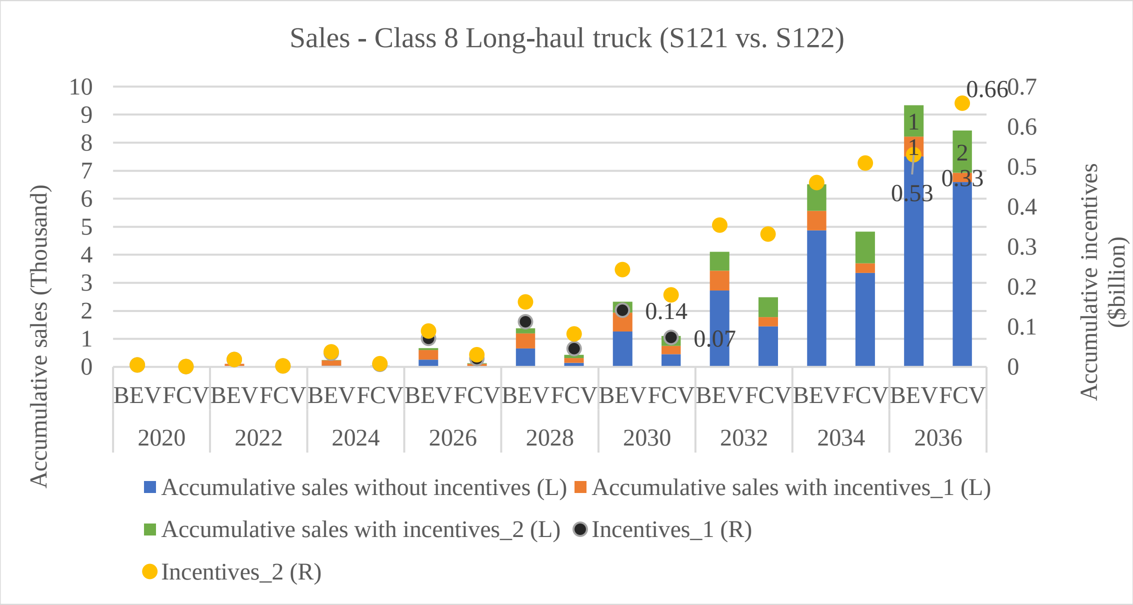


Figure 12. Accumulate sales and incentives under different incentive plans (base infrastructure scenario).

As shown in **Figure 13**, for the market segment for class 3-7 trucks in the scenario of base infrastructure using Incentive Plan 3, a total of 1.4 billion dollars in incentives would generate around 58,000 more BETs, and 11 billion dollars in incentives will generate around 54,000 more FCETs by 2040. For the market segments from class 8, a total of 3.85 billion dollars in incentives would generate around 9,000 more BETs, and 8 billion dollars in incentives will generate around 10,000 more FCETs by 2040.

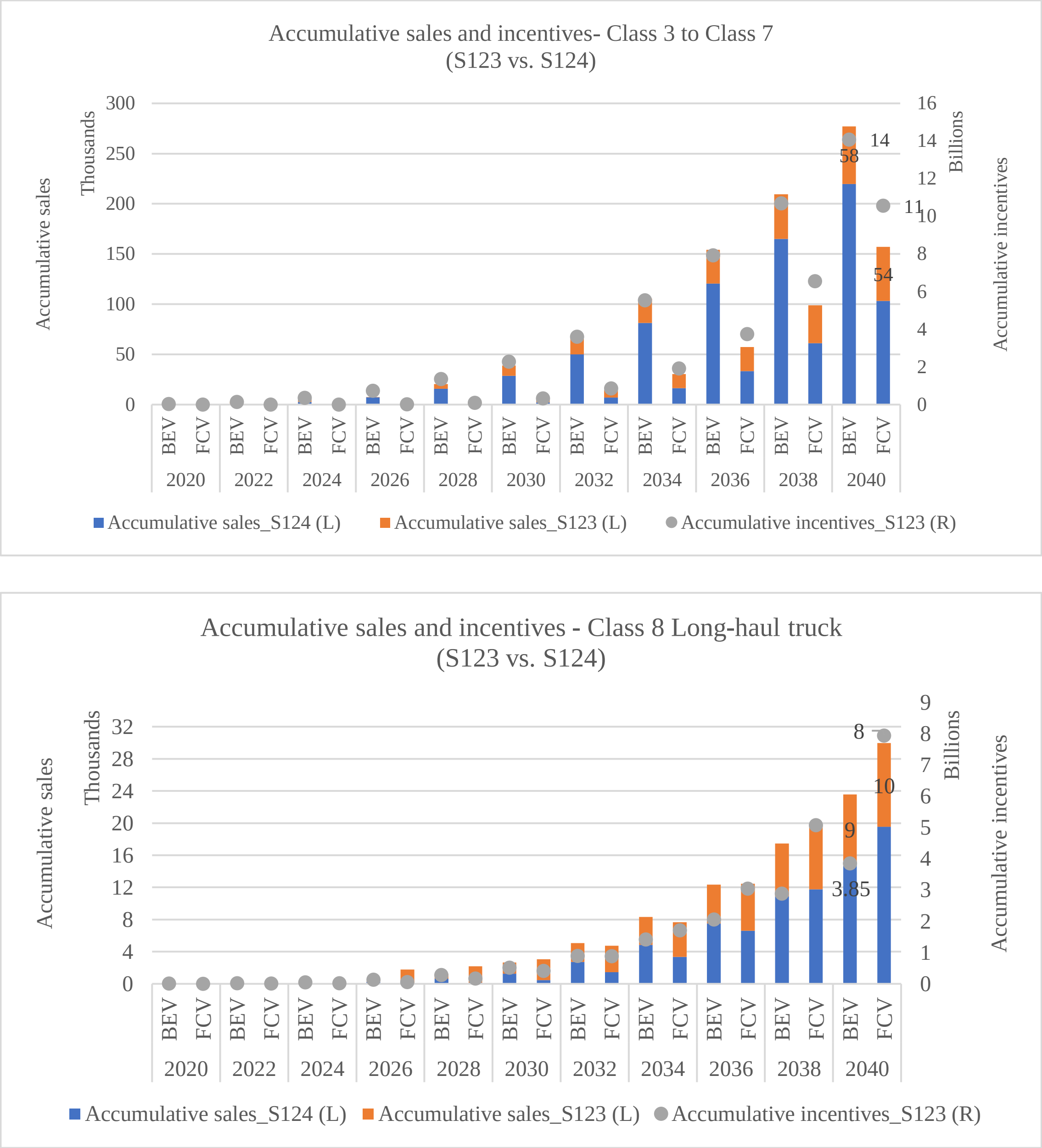
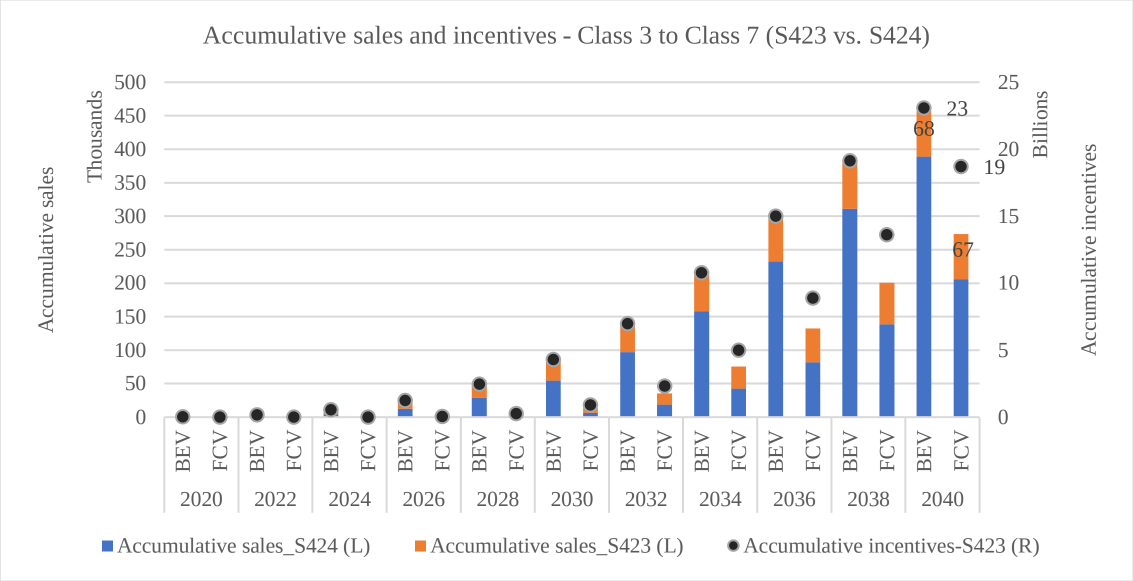


Figure 13. Accumulate sales and incentives with vs. without incentives (base infrastructure scenario).

As shown in **Figure 14**, in the scenario of enhanced infrastructure using Incentive Plan 3, for the market segments from class 3-7, a total of 23 billion dollars in incentives will generate 68,000 more BETs, and 19 billion dollars in incentives will also generate about 67,000 more FCETs by 2040. For the market segments of class 8, a total of 10 billion dollars in incentives will generate 24,000 more BETs, and 22 billion dollars in incentives will also generate about 24,000 more FCETs by 2040.



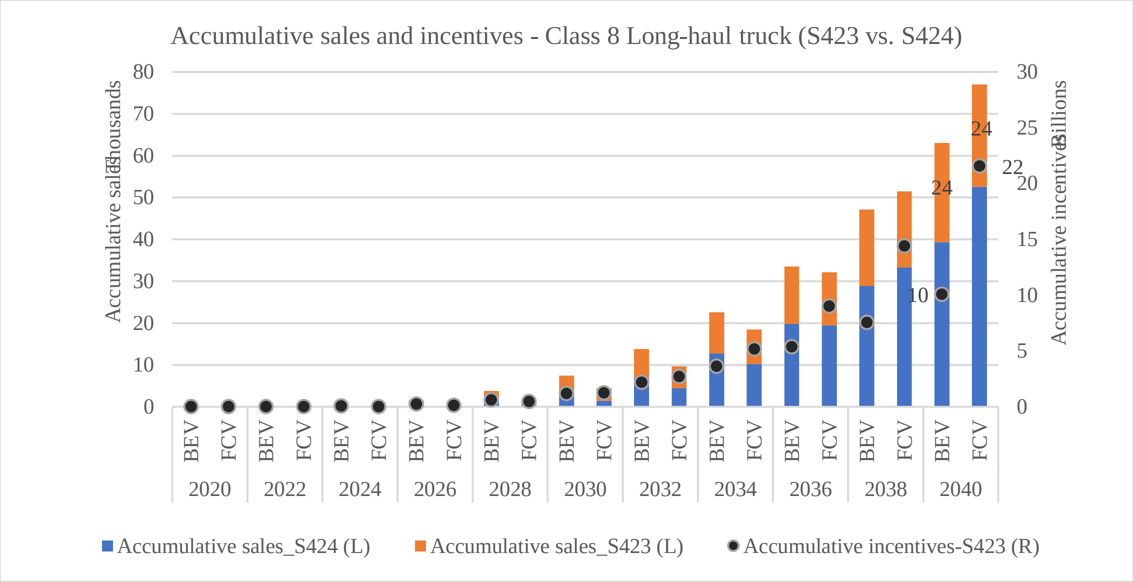


Figure 14. Accumulate sales and incentives under different incentive plans (enhanced infrastructure scenario).

The results just discussed indicate that sales of ZEVs can be enhanced through the implementation of substantial incentives. However, the results show that the increase in market share for trucks under incentive plan 2 (lasting until 2036) is small (less than 2%). The primary reasons for this are: (a) in the early years, incentives alone are insufficient to significantly impact the market penetration of FCETs until the hydrogen infrastructure is adequate to support basic daily operations; and (b) in the later years of incentive plan 2 (after 2030), the incentives are not substantial enough to bridge the gap between ZETs and ICETs.

Therefore, if stakeholders are to see a noticeable positive impact, the incentives after 2035 will be crucial, as illustrated in **Figure 15**. Under incentive plan 3, there could be an increase in the market penetration of FCETs by approximately 6 to 13% compared to scenarios without incentives by 2040, owing to the potential to bridge the gap between ZETs and ICETs. However, the maximum incentives in this strategy will not exceed the currently available sum, including IRS CVTC and HVIP.

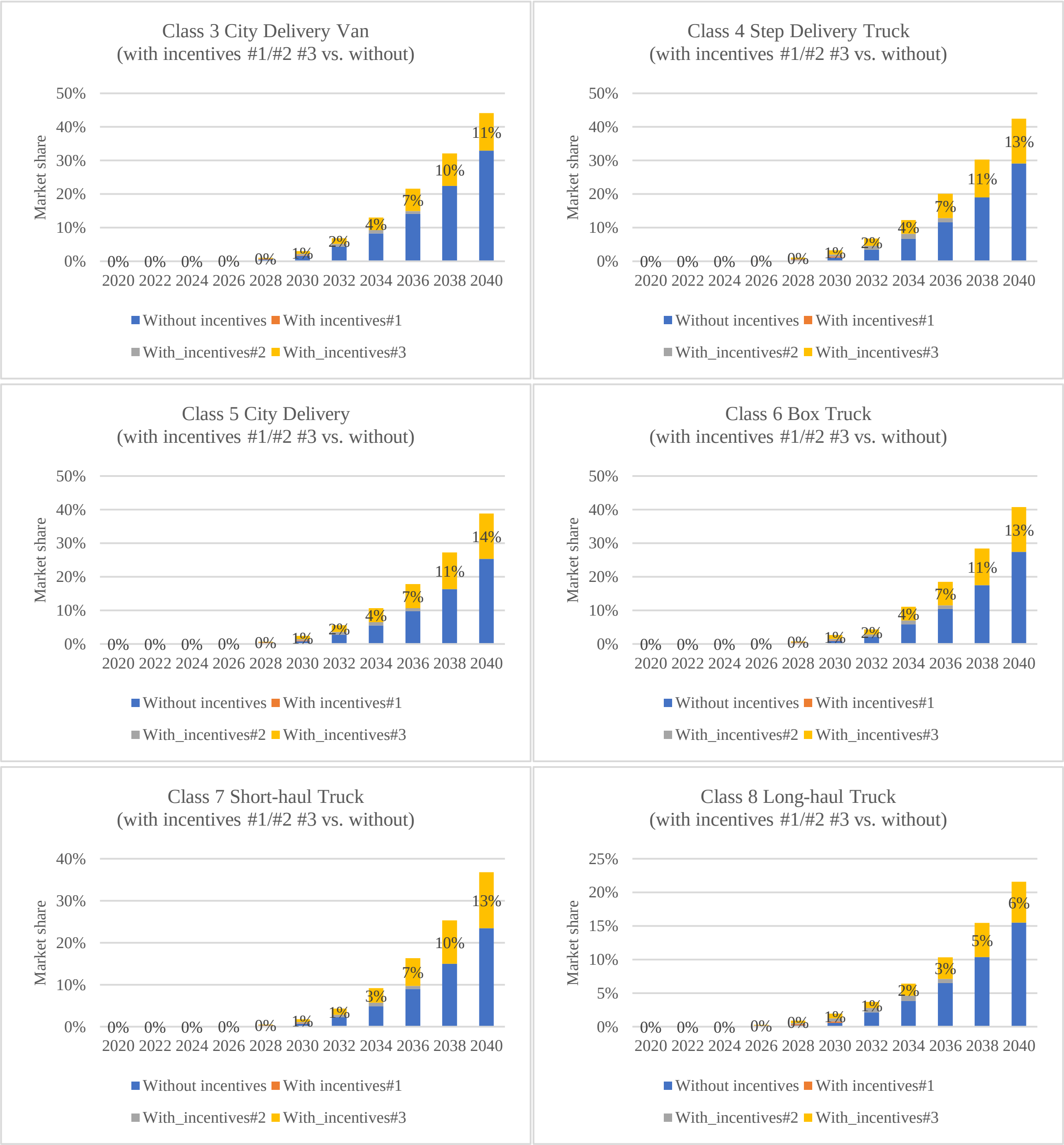


Figure 15. The effect of incentives (plan 3) on the market penetration of FCETs.

7.2 The effect of infrastructure on the FCET

Figure 16 and **Figure 17** compare the sales of Class 3 to Class 8 trucks under two different scenarios, S121 and S321 or S421, from 2020 to 2040, respectively. The prediction shows that in S321, for FCETs from class 3-7, reduced terminal costs and improved hydrogen station availability will enhance the market penetration of FCETs, reaching 222,000 cumulative sales by 2040. For FCETs in the class 8 long-haul truck market, market penetration would reach 33,000 cumulative sales by 2040. Similarly, under scenario S421, both the market for BETs and FCETs increases significantly. For the class 3-7 market, there will be approximately 183,000 more cumulative BET sales by 2040, and approximately 104,000 more cumulative FCET sales by 2040, than the base case. For the class 8 long-haul truck market, there will be approximately 13,000 more cumulative BET sales by 2040, and approximately 4,000 more cumulative FCET sales by 2040 than in the base case.

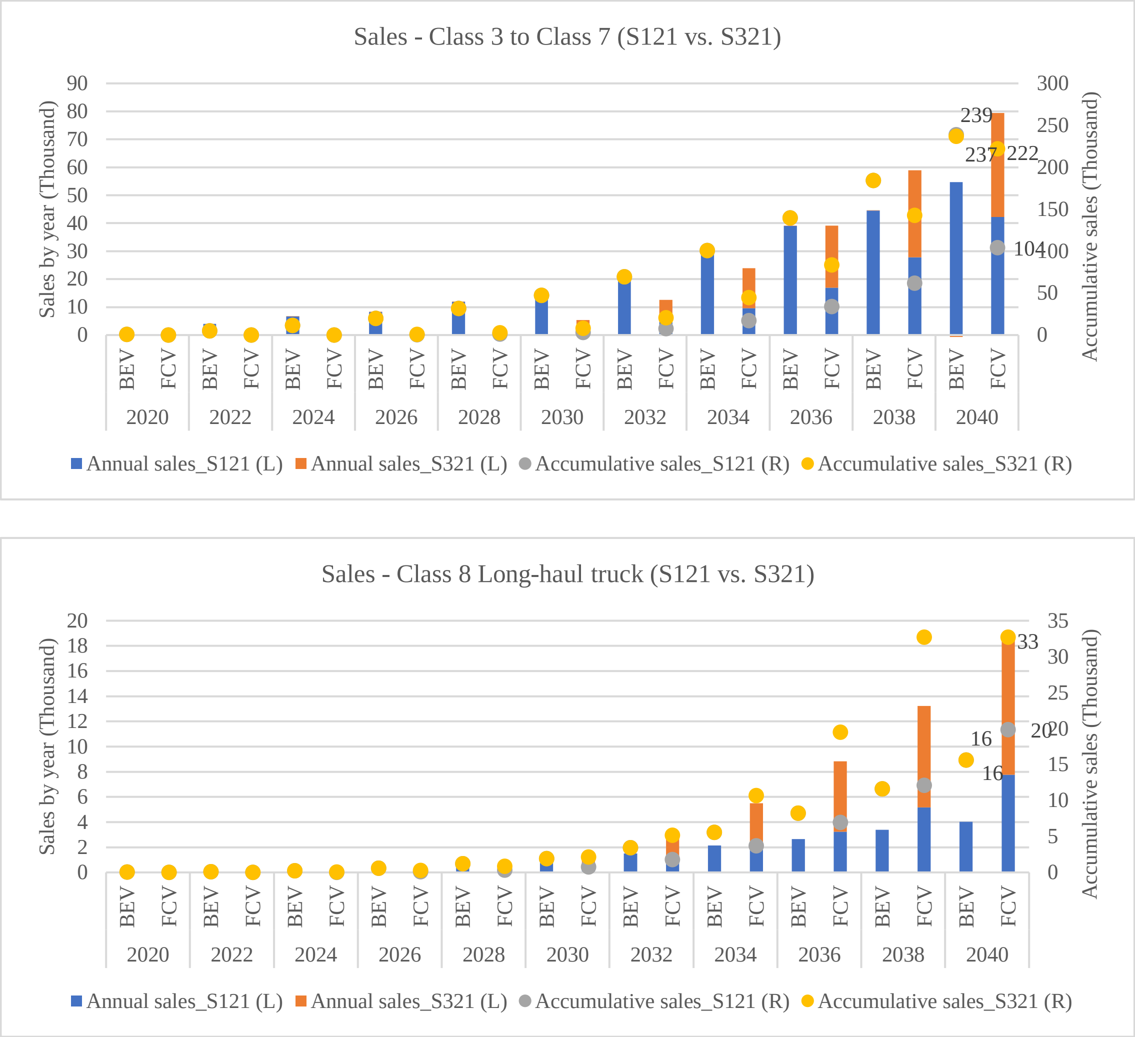
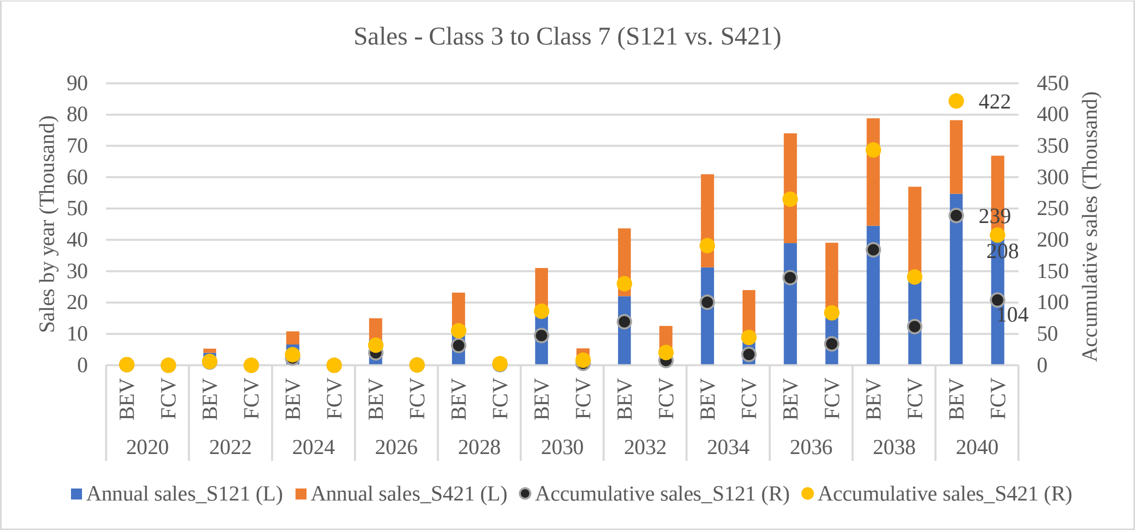


Figure 16. Sales by year and accumulative sales under different infrastructure scenarios.



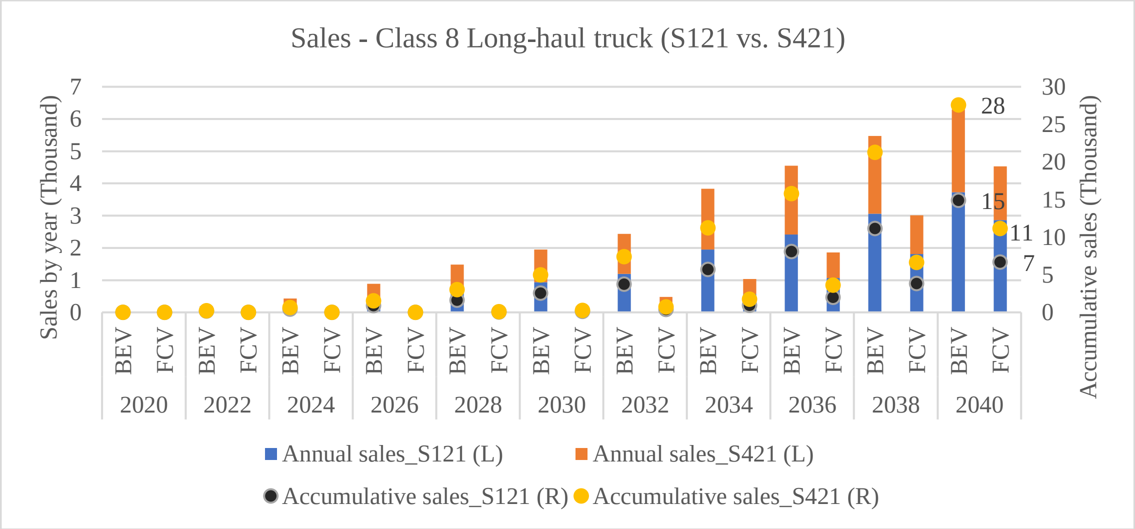


Figure 17. Sales by year and accumulative sales under different infrastructure scenarios.

Figure 18, and **Figure 19** provide a visual representation of sales and market share for BETs and FCETs, respectively, in the form of heatmaps categorized by vehicle class and sales under different scenarios over the next two decades. The progression from lighter to darker shades across the years indicates increasing sales volumes over time for each vehicle class under different scenarios. Both heatmaps provide a quick visual comparison of how different vehicle classes are expected to perform in terms of sales across various scenarios and timeframes. The heatmap with the darker shades indicate higher sales volumes or higher annual market penetration. For instance, in the Class 3 category, sales start at 2893 units (7% market share) in 2020, escalating to a peak of 30,061 units (66% market share) in 2040 under S221, reflecting substantial growth. The figures indicate that Scenario 2 (S2) is the most favorable for the market penetration of BETs, attributed to enhanced charging infrastructure efforts under this scenario. This aligns with the higher sales volumes seen in the BET heatmap where the darker shades, representing increased sales, are most pronounced in the columns under Scenario 2.

The heatmap for FCETs shows a similar trend with color intensity representing sales volume. Starting with modest sales in the Class 3 category, there is a significant increase to 27,965 (61% market share) units by 2040. This pattern of growth is consistent across all classes, with the darkest shades in 2040 signifying the highest sales volumes, notably in the Class 8 category with 9903 (39%) units in the year 2040 and scenario S321/421. For FCETs, Scenario 3 (S3) appears to be the best for market penetration. This is probably because the scenario assumes that efforts have been made to enhance the hydrogen refueling infrastructure, while the charging infrastructure for BETs remains at the base condition (not enhanced). The FCET heatmap reflects this with the highest sales numbers appearing in the columns under Scenario 3, showcasing the darkest shades. Scenario 4 (S4) is a more complex scenario that assumes improvements in both BET charging and FCET hydrogen refueling infrastructures. The impact of this dual-enhancement approach aims to optimize the market conditions for both BETs and FCETs, potentially leading to a more balanced growth in sales for both types of vehicles.

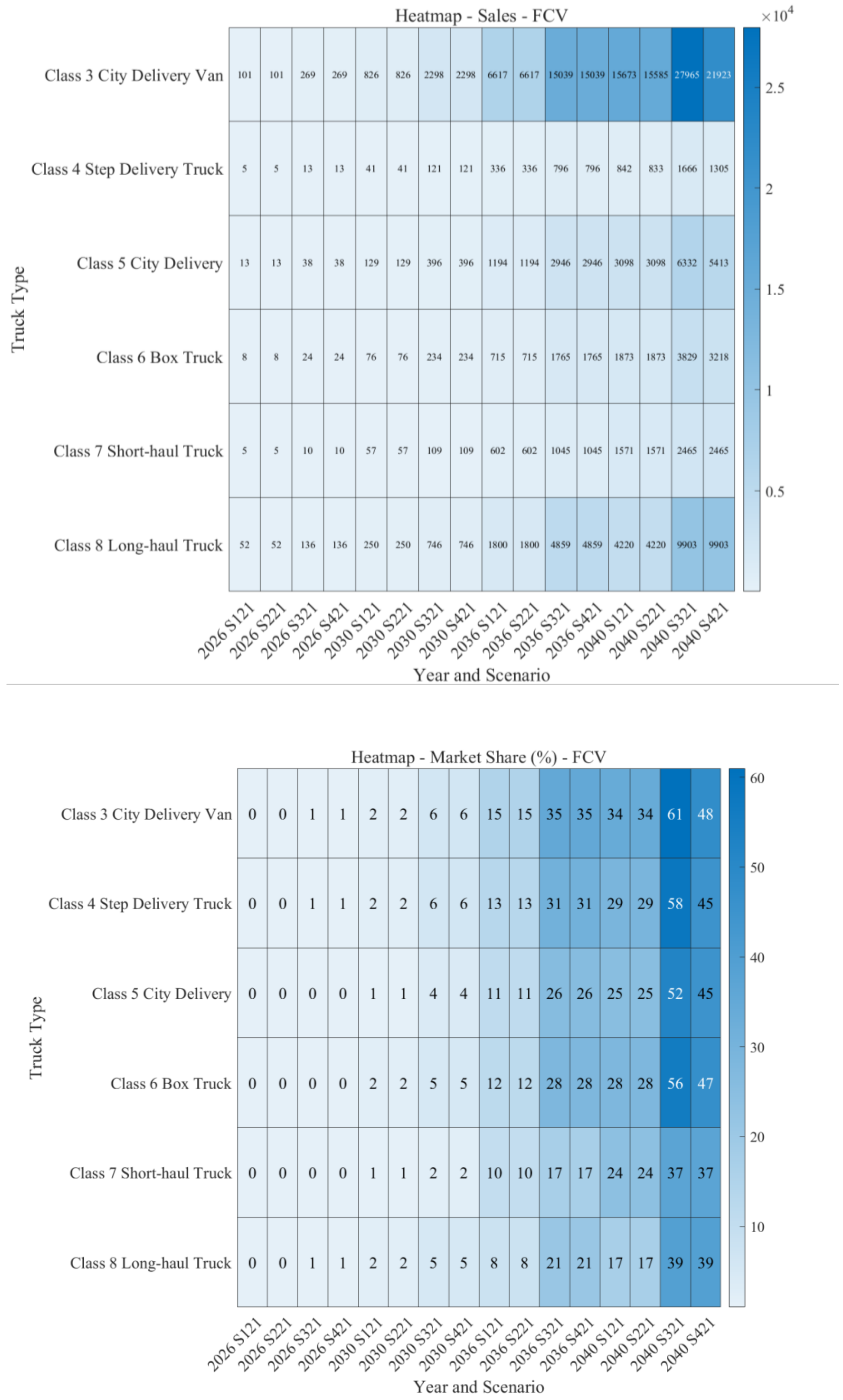
Heatmap - Sales - BEV

Truck Type	2026 S121	2026 S221	2026 S321	2026 S421	2030 S121	2030 S221	2030 S321	2030 S421	2036 S121	2036 S221	2036 S321	2036 S421	2040 S121	2040 S221	2040 S321	2040 S421
Class 3 City Delivery Van	2893	5317	269	5313	5735	11144	5735	11136	13638	24015	13638	25286	18976	30061	17680	23723
Class 4 Step Delivery Truck	216	473	216	409	354	809	354	710	817	1654	817	1557	1146	2044	1146	1573
Class 5 City Delivery	547	1230	547	1066	1021	2409	1021	2116	3065	6378	3065	6013	4403	8122	4403	6750
Class 6 Box Truck	352	793	352	688	679	1602	679	1409	1640	3459	1640	3218	2378	4438	2378	3584
Class 7 Short-haul Truck	260	507	260	507	494	1024	494	1025	1249	2323	1249	2326	1944	3243	1944	3243
Class 8 Long-haul Truck	225	474	225	474	391	994	391	979	1386	3696	1386	3642	2092	5314	2092	5236

Heatmap - Market Share (%) - BEV

Truck Type	2026 S121	2026 S221	2026 S321	2026 S421	2030 S121	2030 S221	2030 S321	2030 S421	2036 S121	2036 S221	2036 S321	2036 S421	2040 S121	2040 S221	2040 S321	2040 S421
Class 3 City Delivery Van	7	13	7	13	15	30	15	30	32	56	32	59	42	66	39	52
Class 4 Step Delivery Truck	9	20	9	17	17	40	17	35	31	64	31	60	40	71	40	55
Class 5 City Delivery	5	12	5	10	11	27	11	24	28	57	28	54	36	67	36	55
Class 6 Box Truck	6	14	6	12	14	33	14	29	26	56	26	52	35	65	35	53
Class 7 Short-haul Truck	5	9	5	9	10	20	10	20	20	38	20	38	29	49	29	49
Class 8 Long-haul Truck	1	2	1	2	2	5	2	5	6	16	6	15	8	21	8	21

Figure 18. Heatmap of sales and market shares of BETs under different scenarios.



Heatmap - Sales - FCV

Truck Type	2026 S121	2026 S221	2026 S321	2026 S421	2030 S121	2030 S221	2030 S321	2030 S421	2036 S121	2036 S221	2036 S321	2036 S421	2040 S121	2040 S221	2040 S321	2040 S421
Class 3 City Delivery Van	101	101	269	269	826	826	2298	2298	6617	6617	15039	15039	15673	15585	27965	21923
Class 4 Step Delivery Truck	5	5	13	13	41	41	121	121	336	336	796	796	842	833	1666	1305
Class 5 City Delivery	13	13	38	38	129	129	396	396	1194	1194	2946	2946	3098	3098	6332	5413
Class 6 Box Truck	8	8	24	24	76	76	234	234	715	715	1765	1765	1873	1873	3829	3218
Class 7 Short-haul Truck	5	5	10	10	57	57	109	109	602	602	1045	1045	1571	1571	2465	2465
Class 8 Long-haul Truck	52	52	136	136	250	250	746	746	1800	1800	4859	4859	4220	4220	9903	9903

Heatmap - Market Share (%) - FCV

Truck Type	2026 S121	2026 S221	2026 S321	2026 S421	2030 S121	2030 S221	2030 S321	2030 S421	2036 S121	2036 S221	2036 S321	2036 S421	2040 S121	2040 S221	2040 S321	2040 S421
Class 3 City Delivery Van	0	0	1	1	2	2	6	6	15	15	35	35	34	34	61	48
Class 4 Step Delivery Truck	0	0	1	1	2	2	6	6	13	13	31	31	29	29	58	45
Class 5 City Delivery	0	0	0	0	1	1	4	4	11	11	26	26	25	25	52	45
Class 6 Box Truck	0	0	0	0	2	2	5	5	12	12	28	28	28	28	56	47
Class 7 Short-haul Truck	0	0	0	0	1	1	2	2	10	10	17	17	24	24	37	37
Class 8 Long-haul Truck	0	0	1	1	2	2	5	5	8	8	21	21	17	17	39	39

Figure 19. Heatmap of sales and market shares of FCETs under different scenarios.

From the perspective of market penetration, establishing a robust hydrogen infrastructure can significantly enhance the market share of FCETs. This relationship is clearly depicted in **Figure 20**, which shows a 15 to 25% improvement in market share with enhanced H2 refueling convenience and reduced terminal costs across different market segments. The development of such infrastructure facilitates greater adoption and utilization of FCETs, directly impacting their visibility and viability in the market.

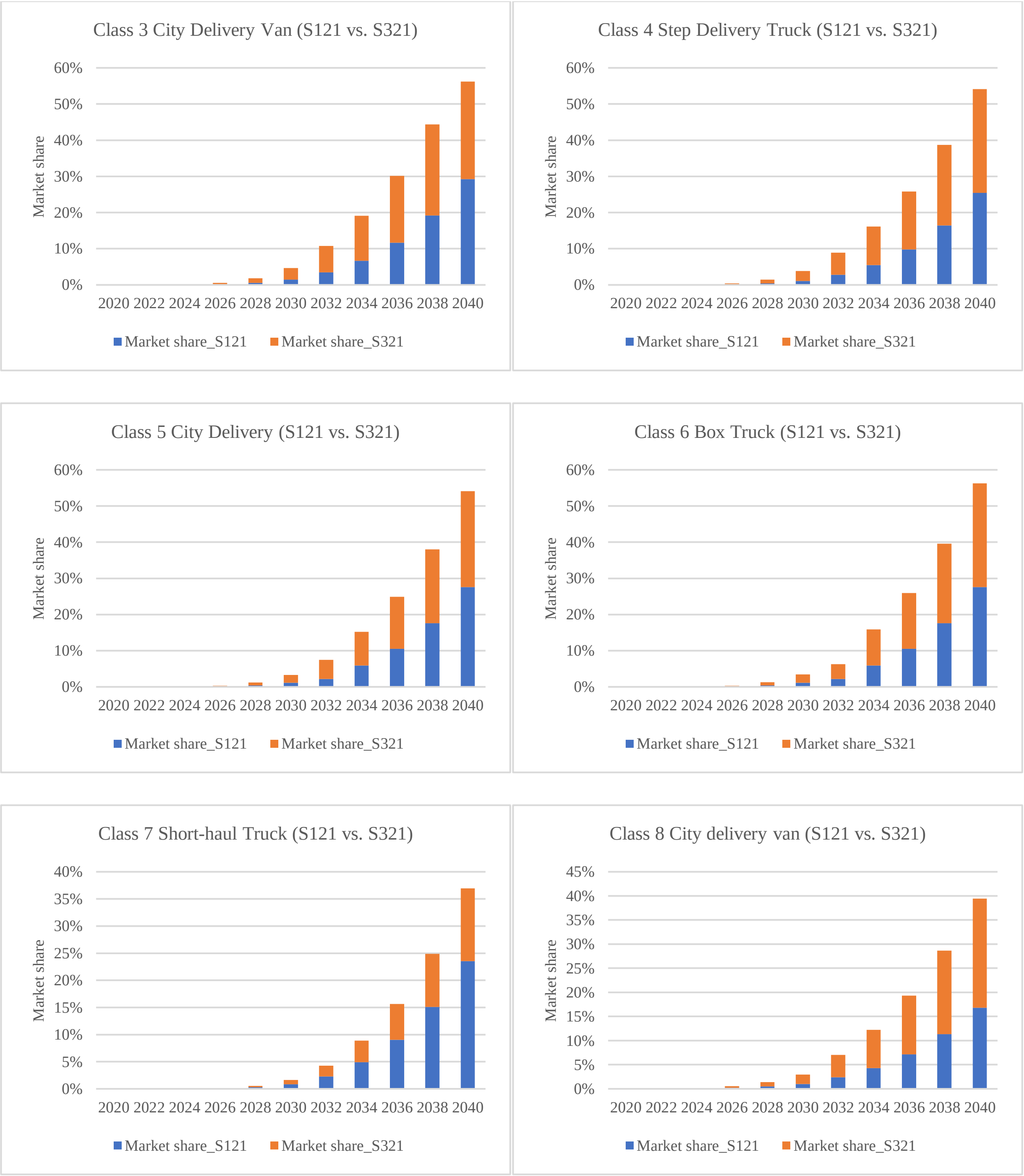


Figure 20. The effect of H2 refueling infrastructure on the market share of FCETs.

7.3 The effect of model availability on the FCET

Figure 21 illustrates the projected market share evolution for various classes of MD/HDVs under the assumption of enhanced infrastructure and reduced terminal costs. It also operates under the premise that, by 2040, the models of FCET will be equivalent to BET in terms of market presence and performance. The transition to ZEVs in the commercial vehicle sector is expected to accelerate due to significant advancements in infrastructure and a decrease in associated terminal costs. Enhanced infrastructure refers to the comprehensive availability and accessibility of charging and refueling stations suitable for electric and hydrogen FC vehicles. As infrastructure improves, it will alleviate range anxiety and operational limitations, encouraging the adoption of ZEVs.

Reduced terminal costs involve the decrease in expenses related to the charging or refueling stations at depots or terminals where vehicles are parked or maintained. This includes the cost of installing and maintaining charging equipment for BETs and refueling equipment for FCETs. As these costs diminish, the TCO for ZEVs becomes more competitive with traditional ICEVs, thereby boosting their market appeal. The graph predicts a significant shift in market share across various truck classes from ICEVs towards BEVs and FCEVs over two decades:

Class 3 City Delivery Vans show a dramatic rise in BEV adoption, overtaking ICEVs by the late 2020s. The graph suggests that city delivery vans are particularly well-suited to early electrification, likely due to their operational patterns of short distances and the ability to return to a central hub for charging.

Class 4 step delivery trucks also show strong adoption of BEVs, with FCEVs beginning to gain market share from the 2030s onward. This trend may be influenced by the increased range and rapid refueling capabilities of FCEVs, making them suitable for step delivery routes that may be longer than typical city deliveries.

Class 5 Step Vans and Class 6 Box Trucks both show a robust increase in BEV market share with a gradual rise in FCEVs. Their adoption curve is more gradual compared to Class 3 and 4, possibly reflecting the greater range requirements and payload capacities that come with these vehicle classes.

For Class 7 short-haul and Class 8 long-haul trucks, the transition to BEVs has been initially slow, reflecting inherent challenges in electrifying vehicles that require high energy inputs and are designed for extended range operations. The vehicle choice model results suggest a gradual but steady rise in EV adoption rates within these categories, underscored by a promising increase in the integration of FCEVs. By 2040, the model indicates that FCEVs have significant potential to capture a substantial portion of the market. This growth is largely attributed to significant technological advancements in FC efficiency and the expanding development of hydrogen fuel infrastructure. However, the Class 8 long-haul truck market presents added difficulties. The primary challenges stem from the need for trucks to maintain long-range capabilities and high payload capacities, which are currently well served by diesel trucks. The projected costs of the long range (>500 miles) class 8 trucks, even FCEVs, is considerably higher than the comparable diesel trucks. In addition, the establishment and maintenance of a comprehensive hydrogen refueling network are imperative to support FCEVs, which involves considerable investment and coordination at both the industrial and governmental levels. As such, while there is a clear trajectory towards electrification and the use of hydrogen FCs, the pace of adoption in this segment is contingent upon overcoming these substantial barriers.

In short, the projected market shares indicate a dynamic and transformative phase for the truck market, moving away from ICEVs towards a future dominated by electric and hydrogen FC technologies. This transition, supported by improvements in infrastructure and reductions in terminal costs, is expected to make ZEVs more viable and widespread by 2040, with different vehicle classes following a distinct path based on their specific operational needs and technological developments.

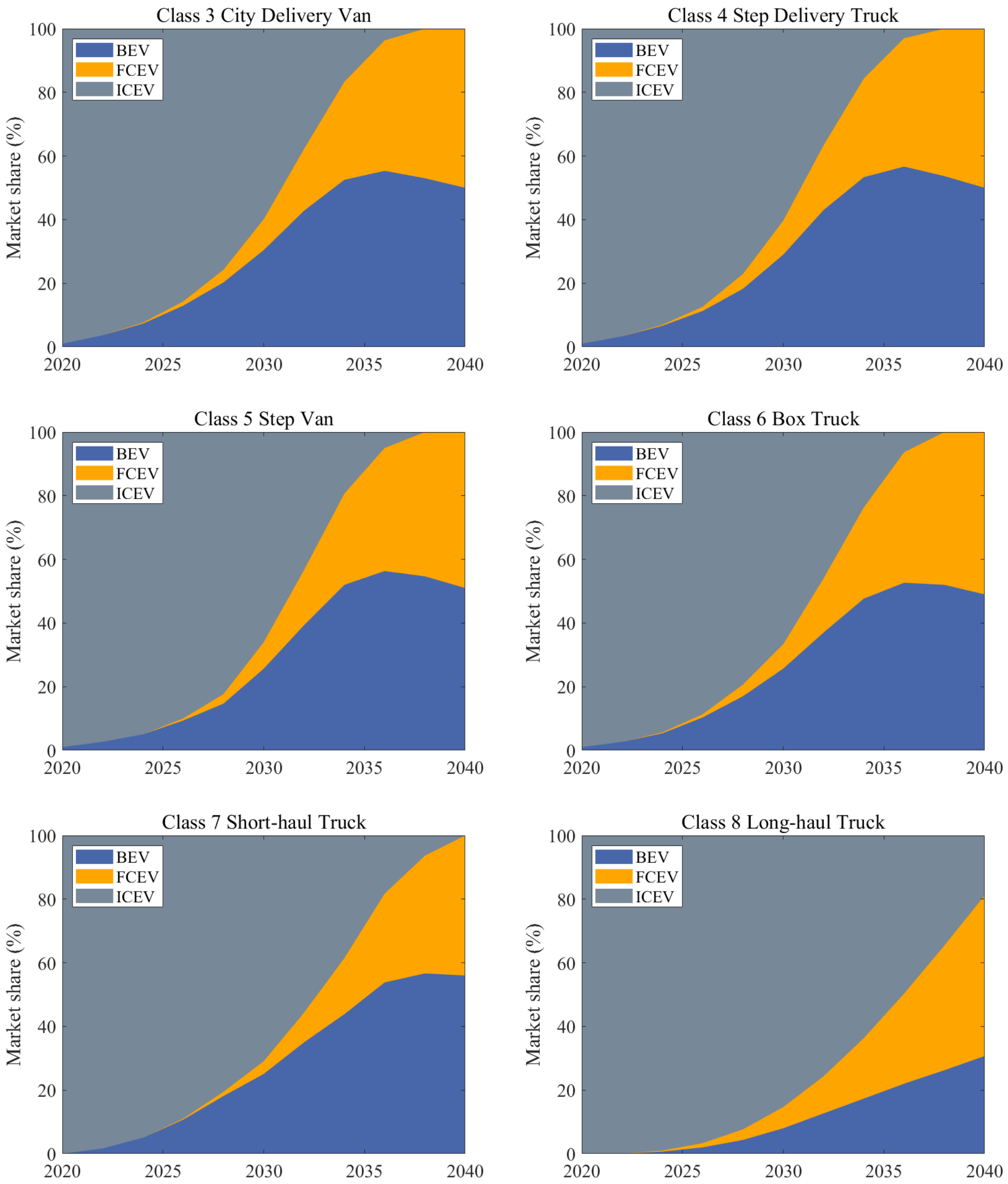


Figure 21. Market share of ZEVs and ICEVs under H2+ conditions (incentive plan #3, enhanced infrastructure and improved model availability).

8 Prospects for market penetration of fuel cell electric trucks across various classes

The markets prospects for FCETs across different truck classes—MDVs and HDVs—are shaped by a combination of factors including technology and cost advances, regulatory frameworks, infrastructure development, and availability of models. Unless most of these changes in market conditions occur, sales of FCETs will remain low. The results in this study can best be interpreted as how FCET sales are projected to respond to changes in market conditions. Each vehicle class faces unique challenges and opportunities in the transition to hydrogen FC technology, reflecting the diverse requirements and operational contexts of these vehicles. In addition, MD/HDVs are commercial vehicles for which the economics and the reliability and durability of their operations are critical. This makes the competition of FCETs with BETs difficult when BETs are available for purchase that meet the operational requirements of truck purchasers.

8.1 MD FCET

MDVs are well positioned to utilize FC powertrains given their modest vehicle costs and operational characteristics. MDVs, such as delivery trucks, work vans, and smaller buses, typically operate within relatively short routes, requiring less than 10 kgH2 per day. This makes their refueling at private terminals or public refueling stations convenient and inexpensive. Battery-electric MDVs are likely to be lower cost to purchase and lower cost to operate with electricity readily available and less costly than H2. MDV applications requiring near 24-hour operation would benefit from the short refueling time of FC vehicles and be suitable applications for FCETs. The vehicle cost model results for MDVs (Class 3-6) indicate when the market conditions for the sale of FCETs in competition with comparable BETs will be reasonable, but not necessarily that MD truck purchasers will prefer the MD FCETs.

8.2 HD FCET

The HDV sector is thought by most experts to be the most likely sector for the use of FCETs, due to the need for long range daily use on a regular basis. This is the case for long haul, freight trucks. This application will be difficult to meet with BETs, even with opportunity charging available along highways. In addition, the purchase cost of HD BETs with 500-1000 kWh batteries is likely to be significantly higher than for FCETs with ranges of 500 miles and greater. Further, packaging the large batteries on the tractors of long-haul BETs will be difficult. Regional applications of tractor-trailer HD trucks can also use H2 and FCs with private refueling terminals. Hence the vehicle choice results for HD Class 8 tractor-trailer ZEV trucks project what market conditions are needed to produce high sales of FCETs in competition with BETs by 2030 and beyond.

9 Summary and Conclusions

Medium- and heavy-duty FCETs will face a tough challenge competing for market share against BETs and ICEVs between 2025 and 2040. The core obstacles identified—such as high costs, limited model availability, slow development by major manufacturers, and nascent hydrogen infrastructure—present significant hurdles for the widespread adoption of FCETs. Additionally, competitive advancements in the BET sector, coupled with improvements in diesel engine efficiency, place further pressure on fuel cell technologies to demonstrate clear and sustainable advantages. Herein, the report outlines critical benefits of FCETs, indicating areas of opportunity for this technology to contribute to the California Air Resources Board's target of 100% ZEVs by the 2040s across different truck segments. These include long-range capabilities, acceleration and braking performance comparable to BETs, potentially greater durability, lower initial costs, and the rapid refueling times offered by hydrogen. These advantages are notable compared to their electric counterparts, while superior driving performance and environmental contributions stand out against diesel alternatives. Additionally, the possibility of integrating hydrogen refueling infrastructure within private terminals and the lower impact of extreme weather conditions on FCET operations enhance the value proposition of fuel cells. The storage and transportation of large energy quantities as liquid hydrogen could also present economic benefits over battery-electric storage solutions, given advancements in logistics and LH2 refueling technologies, such as cryogenic pumps.

Our vehicle cost model shows that for MDTs, the fuel cell system accounts for about 40% of the total vehicle cost before 2030, with the potential to decrease to around 30% by 2040. For HDTs, such as Class 8 long-haul trucks, the fuel cell system is expected to decline and account for approximately 20% of the total vehicle cost by 2040. Initial cost comparisons indicate that neither FCETs nor BETs are likely to match the cost of ICEVs by 2040, even with minimal markup, particularly in the Class 8 heavy-duty truck market. However, when considering the TCO, both medium-duty FCETs and BETs have the potential to approach or even fall below the cost levels of diesel trucks within the next two decades, benefiting from lower fuel costs, reduced maintenance expenses, and greater energy efficiency. For Class 8 heavy-duty long-haul vehicles, FCETs are expected to have a lower TCOs than BETs will. However, achieving cost parity with diesel trucks by 2040 will remain challenging due to the higher upfront costs. Looking ahead to 2030–2040, heavy-duty FCETs have the potential to outperform BETs in initial cost across all mileage ranges, particularly for distances exceeding 400 miles.

The current procurement incentive policy in California (IRS/CVTC + HVIP) has a strong potential to bridge the cost gap between FCETs and ICEVs from 2028 to 2032 across different MHDV market segments, provided there are no cuts in the coming years. However, procurement incentives alone are unlikely to drive significant market penetration of FCETs in the early years, before infrastructure meets basic convenience requirements. Substantial incentives would have a much greater impact in the later years (after 2030), as they have the potential to cover a significant portion of the cost gap between FCVs and ICEVs.

In conclusion, commercially available FCET models across different market segments play key roles in breaking the ice. Infrastructure—including H2 refueling terminals for Class 3 to Class 7 trucks and public stations for Class 8 long-haul trucks—plays a pivotal role in the market penetration of FCETs. The MD FCETs lack the technological and market maturity of the MD BETs. However, in the HDV market, FCETs have a great chance to gain significant market share or even dominate the market over BETs due to faster refueling times and longer driving ranges. Achieving the CARB's goals will require a combination of measures, rather than a single effort. This combination includes technological advancements to reduce truck costs, infrastructure establishment (based on specific market application scenarios, such as terminals or public stations), and robust policy intervention to address a significant portion of the gap between FCETs and ICEVs.

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