White Paper

Roadmap to Fuel Cell Electric Truck Commercialization

California Market Assessment

Sponsored by Southern California Gas Company and Cummins Electrified Power NA, Inc.

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CALSTART

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List of Acronyms

Acronym	Definition
AB	Assembly Bill
ACF	Advanced Clean Fleets (regulation)
ACT	Advanced Clean Trucks (regulation)
AFC	Alternative Fuels Corridor
BET	battery-electric truck
BTM	behind-the-meter
CAISO	California Independent System Operator
CAPEX	capital expenditures
CARB	California Air Resources Board
CEC	California Energy Commission
CERP	Community Emission Reduction Plan
CHP	California Highway Patrol
CNG	compressed natural gas
CO	carbon monoxide
CO2	carbon dioxide
DMS	Division of Measurement Standards
DOE	U.S. Department of Energy
DOT	U.S. Department of Transportation
EMFAC	Emission Factor Calculator
EnergIIZE	Energy Infrastructure Incentives for Zero-Emission Commercial Vehicles
EPA	U.S. Environmental Protection Agency

Acronym	Definition
EV	electric vehicle
FAF4	Freight Analysis Framework 4
FAST	Fixing America's Surface Transportation Act
FCEB	fuel cell electric bus
FCET	fuel cell electric truck
FCEV	fuel cell electric vehicle
FHWA	Federal Highway Administration
g/s	grams per second
GHG	greenhouse gas
GREET	Greenhouse gases, Regulated Emissions, and Energy use in Technologies Model
GVWR	gross vehicle weight rating
HD	heavy-duty
HRI	Hydrogen Refueling Infrastructure Credit
HVIP	Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project
HyStEP	Hydrogen Station Equipment Performance
IIJA	Infrastructure Investment and Jobs Act
kg	kilogram
kW	kilowatt
kWh	kilowatt-hour
LCFS	Low Carbon Fuel Standard
M2FCT	Million Mile Fuel Cell Truck Consortium
MHD	medium- and heavy-duty
MMBtu	Million British Thermal Units

Acronym	Definition
NACFE	North American Council on Freight Efficiency
NEVI	National Electric Vehicle Infrastructure Program
NOx	nitrogen oxides
NREL	National Renewable Energy Laboratory
OEM	original equipment manufacturer
OPEX	operational expenditures
PEMFC	proton exchange membrane fuel cell
PM	particulate matter
PRHYDE	Protocol for Heavy-Duty Hydrogen Refueling
RFSP	Renewable Fuel Standard Program
RIN	Renewable Identification Number
SB	Senate Bill
SCAQMD	South Coast Air Quality Management District
SMR	steam methane reforming
SOEC	solid oxide fuel cell
SR	State Route
TCO	total cost of ownership
TRL	technology readiness level
WCWLB	Wilmington, Carson, West Long Beach
ZET	zero-emission truck

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Executive Summary

Class 8 fuel cell electric trucks (FCETs) will play a critical role in decarbonizing the freight industry and combating the detrimental effects of climate change. In California, Class 8 trucks represent 12% of Class 2b–8 medium- and heavy-duty (MHD) vehicles, but most of these vehicles are powered by diesel and produce a disproportionate amount of harmful emissions—nearly 20% of transportation-related greenhouse gas (GHG) emissions, nearly 8% of total GHG emissions, and nearly 48% of nitrogen oxides (NOx) emissions [CARB, 2019; CARB, 2022]. Electrifying Class 8 trucks will be important for California to meet its emissions reduction and climate change goals.

> *Class 8 FCETs currently face a causality dilemma: with few trucks deployed as of 2022, hydrogen infrastructure providers will not make significant investments, yet truck manufacturers are hesitant to develop commercial FCETs without public hydrogen infrastructure in place.*

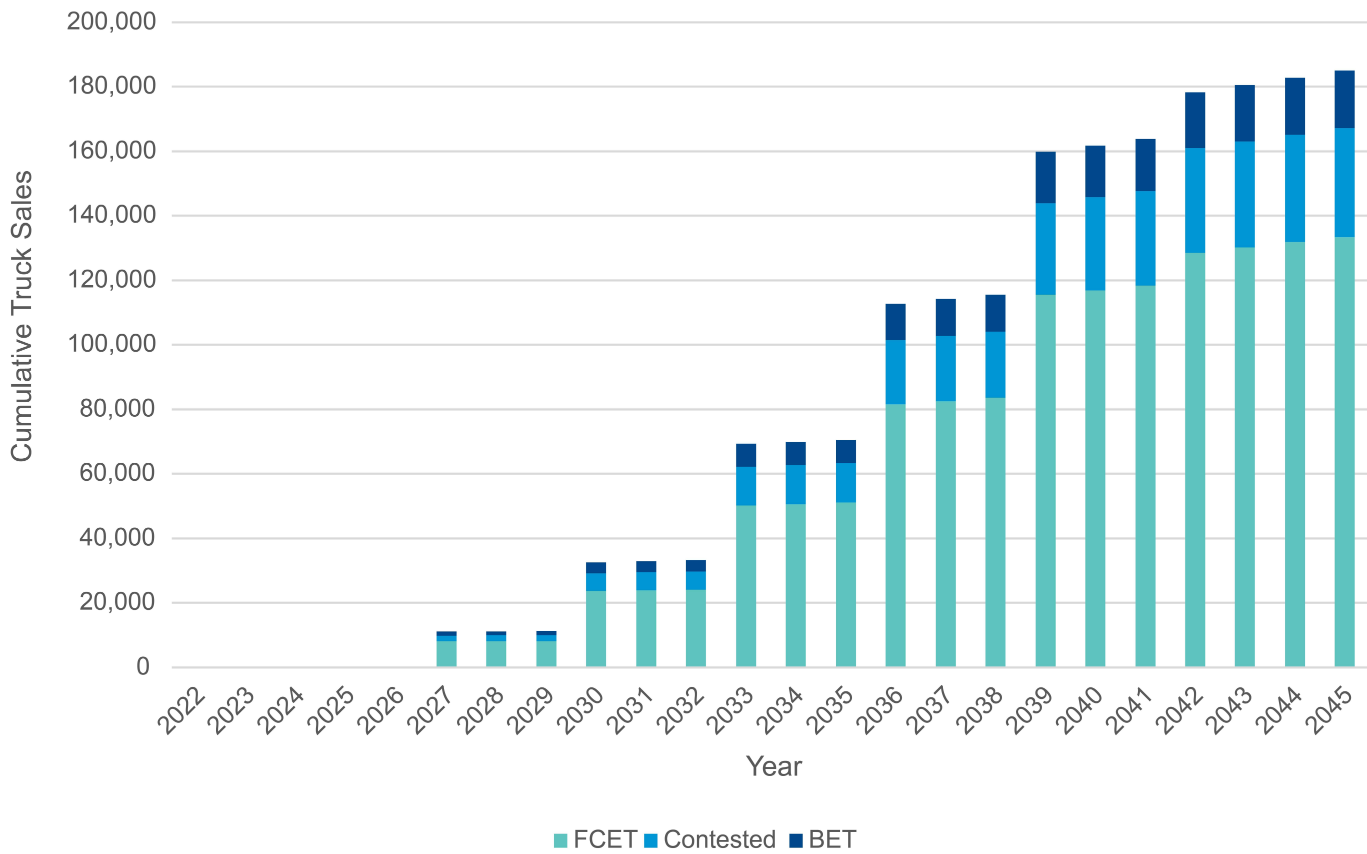
FCETs can serve longer routes and refuel in minutes, meaning these vehicles can successfully complete duty cycles less suited for battery-electric trucks (BETs). However, FCET technology is currently experiencing a causality dilemma. At the time of writing, only 84 Class 7–8 zero-emission trucks (ZETs)—both BETs and FCETs—have been deployed in the United States [Al-Alawi, 2022]. Fleets owners are hesitant to purchase FCETs until hydrogen fueling infrastructure is in place, yet hydrogen infrastructure providers will not move the needle to invest with so few deployments to date. At the same time, truck manufacturers are hesitant to commit to developing commercial FCET products without some degree of certainty that public hydrogen infrastructure will be developed in parallel and that the price of hydrogen will come down with scale.

Estimating the opportunity for Class 8 FCET sales in California can help original equipment manufacturers (OEMs), fleets, and governments evaluate the future size of the market both within the state and nationwide. For this reason, CALSTART projected the total size and annual sales of California's Class 8 ZET market (Figure ES-1)[1] using the California Air

[1] See **Appendix A. Research Methodologies** for additional detail on data sources and the methodology used to develop Figure ES-1.

Resources Board's (CARB's) Large Entity Reporting data, Freight Analysis Framework 4 (FAF4) data,[2] and proposed Advanced Clean Fleets (ACF) regulation compliance targets.

Figure ES-1. Class 8 FCET Cumulative Projected Sales in California



These projections assume that there will be a contested market in which neither BETs nor FCETs will dominate; FCETs and BETs will have to compete for market share. Assuming BETs claim the contested market share, a low-uptake scenario for Class 8 FCETs would result in cumulative sales of 133,458 vehicles by 2045. However, a high-uptake scenario, assuming FCETs claim the entire contested sector, would result in cumulative sales of 167,255 vehicles by 2045. The uptake of BETs and FCETs in the next several years may determine truck sales for decades to come. This contested market share will be determined by whether early

[2] FAF4 provides a comprehensive picture of ton-miles of goods transported by truck in California. A ton-mile equals one ton traveling one mile.

A low-uptake scenario for Class 8 FCETs would result in cumulative sales of 133,458 vehicles by 2045. A high-uptake scenario would result in cumulative sales of 167,255 Class 8 FCETs by 2045. The uptake of BETs versus FCETs in the next several years may determine truck sales for decades to come.

developments begin to take place to overcome high upfront vehicle prices, the current high price of hydrogen, the lack of a hydrogen fueling network, and faster charge times for FCETs.

This report is divided into two separate yet intrinsically linked roadmaps to accelerate FCET adoption in California: the FCET Commercialization Roadmap and the Hydrogen Infrastructure Roadmap. These roadmaps were developed in support of Cummins Electrified Power NA Inc.'s forthcoming demonstration of four Class 8 FCETs to advance the commercialization of heavy-duty (HD) fuel cell drivetrains (funded by the California Energy Commission (CEC)) and CALSTART's research into California's FCET market to understand the drivers and barriers to commercialization. This market transformation is expected to take place in four phases:

1. Introduction Phase: Phase 1 is marked by small-scale demonstrations from 1–20 trucks and an undeveloped HD hydrogen fueling network. OEMs will likely have to provide hydrogen for the demonstration trucks or install temporary fueling stations. The FCET market is currently in this phase, with only small demonstrations and four permanent HD stations in California.
2. Development Phase: Phase 2 is marked by medium-scale demonstrations of more than 20 trucks and hydrogen infrastructure initiated with government assistance and funding. The start of the development of a hydrogen fueling network with government assistance began with CEC's funding awards under GFO-19-602 to develop five HD fueling stations that will come online in 2023 and 2024 [CEC, 2020]. The NorCAL Zero-Emission Regional Drayage Project, also funded by CEC and CARB, will demonstrate 30 Hyundai FCETs at the Port of Oakland as well as one HD fueling station [CEC, 2020a]. This project will begin in 2023; Phase 2 is therefore expected to begin in 2023.
3. Growth Phase: Phase 3 will begin when customers start purchasing FCETs without government demonstration funding. FCET market growth will begin in applications that are easiest to adopt FCETs, mainly regional-haul and return-to-base operations; the lack of hydrogen fueling network will restrict growth.
4. Mature Phase: In Phase 4, FCETs will be used in all feasible applications including long-haul applications. FCETs will expand beyond port/warehouse concentrated areas,

and the emergence of a statewide hydrogen fueling network will allow FCETs to operate in long-haul applications.

In total, the two roadmaps propose six recommendations with corresponding action items for governments, hydrogen producers and providers, financers, OEMs, and fleets to help accelerate FCET technology to market maturity. These two roadmaps are based on the market achieving economies of scale and the implementation of government support for the industry. Given that these factors are more important than time, this report does not provide projections for when the market will transition to Phase 3 (Growth) or Phase 4 (Maturity).

FCET Commercialization Roadmap

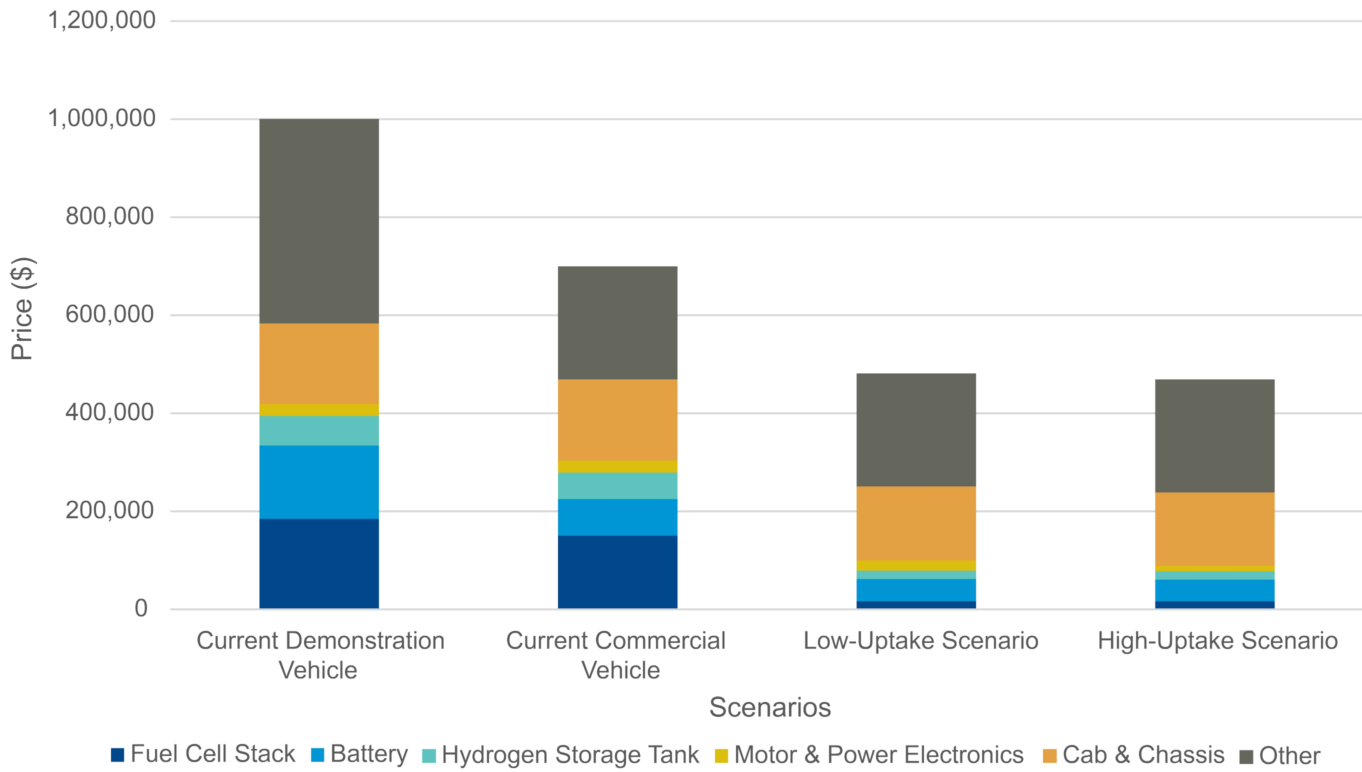
While Class 8 FCET technology has matured and improved significantly over time, these trucks are still in earlier stages of development compared to other zero-emission vehicles. Furthermore, technological maturity does not automatically equate to commercial readiness. Non-technical factors must be addressed to prepare the market for FCET adoption. This study has identified three broad recommendations and corresponding action items to help accelerate FCET commercialization.

Reduce Upfront Costs and Total Cost of Ownership

Concerns about high upfront costs and uncertainty with respect to total cost of ownership (TCO) for these vehicles were raised repeatedly by fleet owners interviewed for this project. Based on interviews with OEMs, CALSTART found that a demonstration Class 8 FCET—a vehicle in the pilot stage of development and produced in low quantities—costs approximately $1 million per vehicle. The average cost of a commercial Class 8 FCET is approximately $700,000, a significant premium over a new diesel truck priced at approximately $150,000. FCET component costs must decrease to reach cost parity with diesel. In 2019, the U.S. Department of Energy (DOE) released targets for Class 8 FCETs that call specifically for reductions in fuel cell system and onboard hydrogen storage costs, the vehicle's most expensive zero-emission components. Moreover, since there have been few FCET demonstrations to date, there is still uncertainty on total maintenance costs for these vehicles, as well as possible residual value. These TCO sensitivities cannot be determined until more FCETs reach the end of their life cycle. CALSTART modeled the impact of economies of scale on the cost of these components and found that costs will decrease dramatically (Figure ES-2).[3]

[3] The methodology for this analysis can be found in **Appendix C. Class 8 FCET Costs**.

Figure ES-2. Projected Class 8 FCET Vehicle Prices



Price decreases substantially during the transition from a demonstration vehicle to a commercialized vehicle due to standardized components and an established manufacturing process. But as shown above, further decreases in Class 8 FCET price can be achieved through economies of scale experienced in both low- and high-uptake scenarios. More sales will assist in reducing the price of vehicle components, but additional action must be taken to meet DOE targets and further decrease the upfront cost of FCETs.

Action Items

A. **Fund the deployment of 1,000 FCETs** to help increase production and kickstart economies of scale, especially for fuel cells and onboard hydrogen storage tanks. This number of FCETs, a small percentage of Class 7–8 trucks in the state, would accelerate commercialization to Phase 3 (Growth). By using the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) to provide incentive funding of $250 million, or by covering the entire incremental costs of the vehicles with $500 million, the State of California could fund this demonstration for less than the total amount that CEC's Clean Transportation Program has spent [CEC, 2022].

B. **Subsidize FCET leasing options** to reduce higher upfront costs and provide fleet owners with more financial options to obtain these vehicles. Particularly for small fleets that cannot afford the capital investment of ZETs and for large fleets not ready for a full investment in this technology, these financing options may become the standard for decades to come.

Promote Commercial Readiness and User Acceptance

Education is a major non-technical barrier to FCET commercialization. Many fleet owners must be more informed about the technology before purchasing a hydrogen-powered vehicle. The technology must also meet current operational needs to gain user acceptance, so FCETs need the same performance level as fleets' current vehicles at a minimum. Ensuring that FCETs have increased durability and faster refueling times, for which DOE has released performance targets to meet by 2030 and 2050, is vital to promoting user acceptance [DOE, 2019].

Action Items

A. **Develop an FCET loaner program** to provide more access to education and allow fleets to gain operational experience with fuel cell technology.

B. **Fund long-term demonstrations** to gather real-world data on maintenance and repair costs over the lifetime of FCETs.

C. **Determine intermediate fast-flow HD fueling standards** to eliminate interoperability issues resulting from different fueling flow rates.

Address Other Enabling Factors

If enabling factors (i.e., additional barriers to the development and maturity of the FCET market) are addressed, fleets will be able to deploy FCETs faster and more efficiently. If no action is taken, these factors, which include weight penally, lack of specialized workforce, and manufacturing, will create severe inconveniences for fleets that can also have financial implications and discourage FCET uptake.

For instance, the federal weight limit of 80,000 pounds gross weight serves to ensure driver safety, but FCETs weigh more than traditional internal combustion engine Class 8 trucks. Fleets will then have to reduce their cargo load to stay within the weight limit. California has issued an exemption that increases the weight limit to 82,000 pounds for ZETs. However, FCETs weigh about 5,000 pounds more than diesel trucks, meaning the incremental weight is greater than this 2,000-pounds exemption. As a result, FCETs will still incur a 3,000-pounds weight penalty or must reduce the amount of cargo they carry to stay under this weight limit.

In addition, the current workforce lacks experience with electrified drivetrains and requires training to repair and maintain this technology. An industry-wide lack of both vehicle engineers and vehicle technicians has led to backlogs of maintenance requests, which will only increase as more zero-emission vehicles are deployed without the development of a specialized workforce.

Lastly, manufacturing is a major constraint on FCET deployments. Since FCETs are currently being manufactured in low quantities, industry's ability to meet market demand is a legitimate concern. The FCET industry will likely face similar challenges as the zero-emission transit bus sector, which has experienced growing backlogs due to supply chain disruptions caused by the COVID-19 pandemic and the Ukraine-Russia war [Zukowski, 2022]. Making investments in FCET manufacturing ahead of market demand is risky for OEMs—the market may take longer than expected to reach the estimated demand or might fail to meet the projected demand at all. If this scenario occurs, OEMs will have either idle assets or stranded assets. In addition, increased manufacturing for FCETs cannot disrupt OEMs' production processes for other vehicle segments.

Action Items

A. **Incentivize lightweighting technology** to decrease the weight of commercial zero-emission vehicles. These benefits would improve fuel economy and increase the cargo load capacity, allowing ZETs to offset some of the weight penalty.

B. **Fund workforce development initiatives** to develop accreditation programs and research centers to train both vehicle technicians and engineers.

C. **Scale up FCET manufacturing capacity** by adopting parallel assembly line processes. This scalable alternative allows OEMs to produce FCETs with minimal changes to the manufacturing facility or the production of other vehicles, reducing the potential for stranded assets.

Hydrogen Infrastructure Roadmap

California's hydrogen market is still in the early stages of development. While an early mover in the MHD fuel cell electric vehicle market, the State of California must take concerted action to advance the hydrogen production and the MHD hydrogen fueling station markets, especially in order to secure enough hydrogen supplies to serve FCETs and to build a hydrogen fueling network. This study determined three broad recommendations for state and federal governments, financers, hydrogen producers, and hydrogen station developers to help accelerate the development of California's hydrogen infrastructure.

Support In-State, Low-Carbon Hydrogen Production

Class 8 FCET deployments will be constrained by hydrogen availability, which will limit the size of the market. As of 2022, an estimated 61,500 kilograms (kg) per day of hydrogen will be available to the transportation market in California. CALSTART has identified additional hydrogen production projects in coming years, determining that the amount of available hydrogen in 2024 is estimated to be about 119,000 kg per day. Even in a low-uptake scenario, this report shows that demand for hydrogen from Class 8 FCETs will quickly exceed hydrogen production capacity by 2027. A major shortage of hydrogen will occur without an increase in hydrogen production capacity, so constructing new hydrogen production plants, increasing production plant capacity, and/or developing more onsite hydrogen production at fleet depots will be critical to fill this gap.

Action Items

A. **Leverage funding for low-carbon hydrogen production**, which includes seeking federal funding, such as the Hydrogen Hubs solicitation funding made possible by the Infrastructure Investment and Jobs Act (IIJA),[4] and supporting the establishment of the California Clean Hydrogen Hub Fund to finance clean hydrogen production.

B. **Increase renewable hydrogen production** by awarding shovel-ready projects such as CEC's GFO-20-609 Renewable Hydrogen Transportation Fuel Production grant solicitation finalists.[5]

C. **Fund research to make other low-carbon hydrogen production methods economically viable**, such as catalytic dry reforming of biogas to hydrogen, catalytic non-thermal plasma biogas to hydrogen, and other innovative approaches.

Develop a Hydrogen Fueling Network

In addition to production capacity, hydrogen fueling station capacity must also increase substantially to meet future hydrogen demand (Figure ES-3).[6] Current light-duty stations do not have enough storage capacity to fuel HD FCETs at scale, and standards for light-duty fueling are not appropriate or compatible for HD FCETs. At the time of writing, few HD hydrogen fueling stations have been constructed, and most stations have low volume

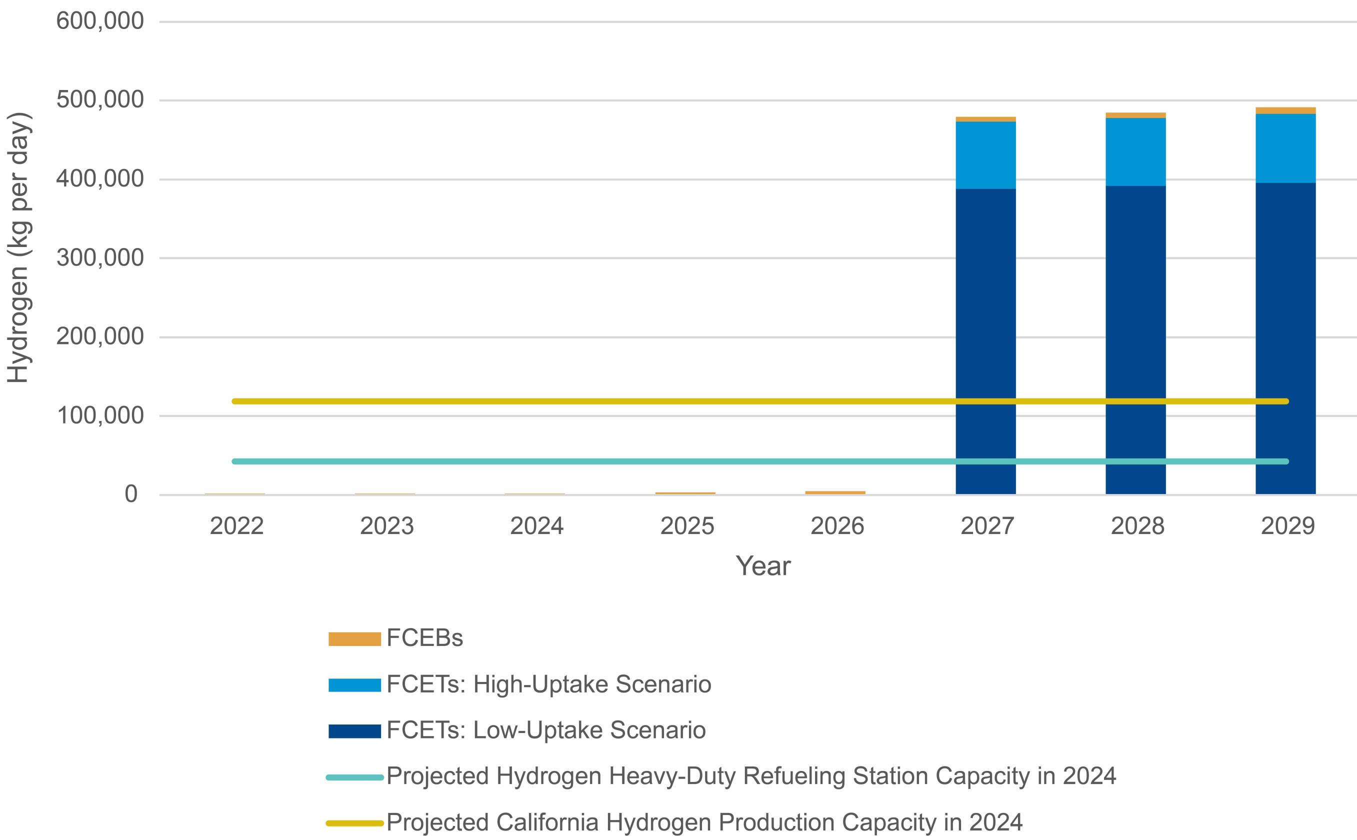
[4] For more information about IIJA, visit https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

[5] For more information about GFO-20-609, visit https://www.energy.ca.gov/solicitations/2021-04/gfo-20-609-renewable-hydrogen-transportation-fuel-production.

[6] The methodology for this analysis can be found in **Appendix F. Hydrogen Demand**.

capacity. The largest planned fueling station in California will have about 6,000 kg per day capacity, but most stations are currently below 2,000 kg per day.

Figure ES-3. Projected Hydrogen Demand for Class 8 FCETs



Action Items

Once the Class 8 FCET market reaches Phase 3 (Growth) and Phase 4 (Mature) of commercialization, these trucks are expected to serve long-haul routes. These applications will require hydrogen fueling corridors for longer trips, meaning a fueling corridor network akin to the current network of truck stops must be developed.

A. **Apply for hydrogen fueling station funding** through Energy Infrastructure Incentives for Zero-Emission (EnergIIZE) Commercial Vehicles and IIJA Alternative Fuels Corridor Funding.

B. **Allocate resources to build retail stations in first-mover clusters** where concentrated deployments of Class 8 FCETs will initially appear (Table ES-1).[7] Developing these clusters is vital to advancing commercialization to Phase 3 (Growth).

Table ES-1. Goods Movement Clusters for Hydrogen Fueling Station Deployment

Cluster	Estimated Fueling Capacity by 2024 (kg per day)	Estimated Demand by 2030 (kg per day): Low-Uptake Scenario	Estimated Demand by 2030 (kg per day): High-Uptake Scenario	Estimated Number of Additional Hydrogen Fueling Stations Required by 2030
Los Angeles-Orange County-Inland Empire	23,500	64,200	175,650	9–31
Bay Area	3,200	5,725	29,350	1–6
Central Valley/SR-99	15,650	41,900	103,700	6–18
San Diego	0	2,800	11,900	1–3

C. **Build out hydrogen fueling corridors** to support long-haul goods movement outside of first-mover clusters along several interstate corridors. These corridors are vital for facilitating the use of FCETs beyond regional-haul applications and into long-haul applications, an important step for advancing commercialization to Phase 4 (Maturity).

D. **Extend the Hydrogen Refueling Infrastructure credits** to incentivize the build out of a hydrogen station network, which will compensate owners for current financial risks of opening a station.

E. **Establish a station testing program** to facilitate the station commissioning process. The State of California developed the Hydrogen Station Equipment Performance (HyStEP) device to accelerate the commissioning process for light-duty hydrogen

[7] See **Appendix G. First-Mover Clusters** for the methodology used to determine these clusters and develop fueling capacity, demand, and fueling station estimates.

fueling stations. A next-generation HyStEP device should be developed to support commissioning for MHD hydrogen fueling stations.

F. **Develop measurement standards testing equipment** to ensure that MHD stations comply with weighing and measuring equipment standards and point-of-sale requirements. MHD stations must show that they comply with these standards to complete the commissioning process. Developing test equipment for measurement standards will accelerate the commissioning process for MHD stations.

Reduce the Price of Hydrogen

The high price of hydrogen compared to both diesel and electricity for BETs is a major barrier to adoption. At the time of writing, the price of retail hydrogen at HD hydrogen fueling stations is between $13 and $16 per kg [CARB, 2021c]. While there are other factors at play, the main driver behind hydrogen's high price is low sales volume. To reach Phase 4 (Maturity), hydrogen will need to achieve price parity with diesel.

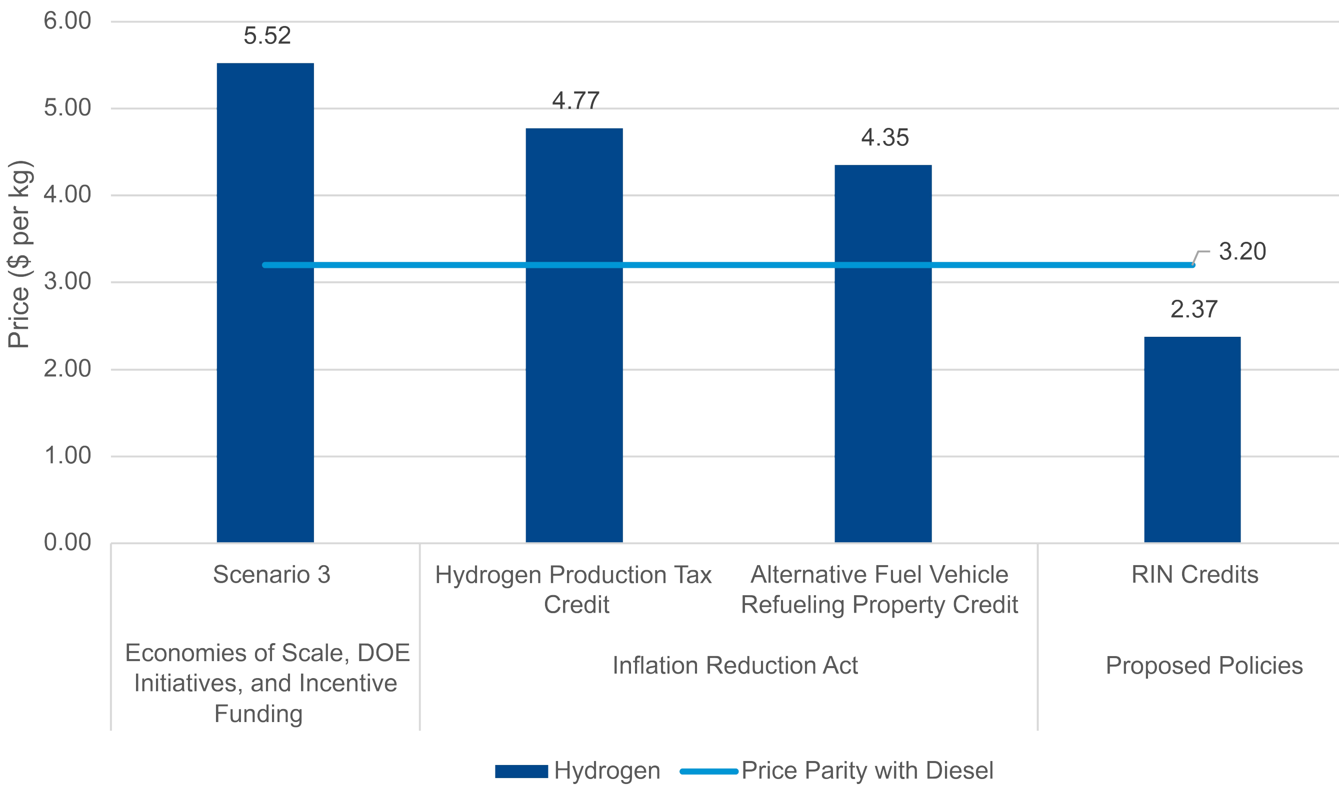
DOE is taking action to help address sales volume through the Hydrogen Earthshot program, which aims to reduce the cost of producing hydrogen to $2 per kg by 2026 and to $1 per kg by 2030 by increasing the technology readiness for low temperature electrolyzers and high temperature electrolyzers to commercialization and therefore enabling mass production of hydrogen [DOE, n.d.]. The Inflation Reduction Act will also reduce the price of hydrogen by providing a production tax credit of up to $3 per kg, depending on the carbon intensity of the production pathway. The cost of hydrogen stations will also need to decrease. Compressors and hydrogen storage tanks are the most expensive items and together constitute nearly half of the station cost. (Compressors and hydrogen storage tanks comprise about 21% and 27% of the station cost, respectively.) These components are manufactured in small quantities, so as more hydrogen stations are built, these components are expected to benefit from economies of scale.

Like compressors and hydrogen storage tanks, the price of hydrogen is expected to decrease as economies of scale are reached. This study's projections indicate that with economies of scale, a decrease in the cost of hydrogen production, and incentive funding for hydrogen stations, the price of hydrogen sold at a retail station can potentially fall to as low as $5.52 per kg. Price decreases of this magnitude would be consistent with the FCET market reaching Phase 3 (Growth), but this price is still higher than the diesel parity price of $3.20 per kg.

Action Items

A. **Modify the Renewable Fuel Standard Program/Renewable Identification Number credits** to include a hydrogen pathway that, combined with the Inflation Reduction Act's Hydrogen Production Tax Credit and the Alternative Fuel Vehicle Refueling Property Credit, will reduce the retail price of hydrogen to less than the cost of diesel (Figure ES-4).[8]

Figure ES-4. Projected Impact of Proposed Policies on the Retail Price of Hydrogen



Conclusion

Based on the commercialization stages outlined in this report, the FCET market in California is currently transitioning from Phase 1 (Introduction) to Phase 2 (Development). Phase 2 will begin with the start of the NorCAL Zero-Emission Regional Drayage Project in 2023. Industry research, development efforts, and government funding for demonstration projects over the last few years has culminated in substantial gains in FCET technology maturity. However, numerous and larger-scale pilot projects are needed to advance the market.

[8] The methodology for this analysis can be found in **Appendix H. Retail Hydrogen Costs**.

Industry will need to prepare markets for hydrogen fuel cell technology in order to advance commercialization to Phase 3 (Growth) and Phase 4 (Maturity). Implementing the recommendations outlined in these two roadmaps will help create pathways to lower the price of the trucks; advance technological development and user acceptance; and address the weight penalty, insufficient workforce, and manufacturing dilemma currently hindering FCET adoption. While early action has been taken to address the market's causality dilemma, this problem will persist until hydrogen production, distribution, and fueling infrastructure is in place to facilitate on-road deployments. Government action will play an important role in rapidly increasing production capacity, building out a hydrogen fueling network, and driving down the price of hydrogen.

I. Introduction

Freight plays a critical role in California's economy. Class 8 trucks are highly utilized to transport goods both throughout the state and across the country. These trucks represent 12% of Class 2b–8 medium- and heavy-duty (MHD) vehicles in California, but most of these vehicles are powered by diesel and produce a disproportionate amount of harmful emissions. Heavy-duty (HD) vehicles are responsible for nearly 20% of transportation-related greenhouse gas (GHG) emissions in California and nearly 8% of total GHG emissions in California [CARB, 2019]. They also produce 48% of nitrogen oxides (NOx) emissions in the state [CARB, 2022]. As a result, transitioning Class 8 trucks to zero-emission technology will help combat climate change and significantly improve air quality.

The deployment of zero-emission trucks (ZETs) is important for meeting California's environmental and climate change goals. Battery-electric trucks (BETs) and fuel cell electric trucks (FCETs) have emerged as zero-emission solutions to diesel-powered Class 8 trucks, but the number of deployed BETs and FCETs at the time of writing is low. As of June 2022, only 84 HD ZETs have been deployed in the United States [Al-Alawi, 2022]. Class 8 trucks are used for a wide range of duty cycles: while many Class 8 trucks operate on a local and regional basis, vehicles traveling long distances contribute a significant fraction of the truck industry's vehicle miles traveled [Union of Concerned Scientists, 2019]. ZETs must be able to replicate the capabilities of a Class 8 diesel truck to be commercially competitive. While the technology continues to improve, BETs can be constrained in some applications by the maximum range that batteries provide. FCETs, however, can complement BETs by serving longer routes and refueling within minutes.

On the other hand, FCETs currently suffer from a causality dilemma. Fleet owners do not want to purchase FCETs until the necessary hydrogen fueling infrastructure network is in place, but hydrogen fuel infrastructure providers are hesitant to invest in refueling stations and equipment with so few trucks on the road. Eliminating this chicken and egg problem will be an integral step for FCET commercialization.

To advance the commercialization of HD fuel cell drivetrains, the California Energy Commission (CEC) provided funding under grant agreement number ARV-16-025 to deploy and demonstrate four Class 8 FCETs for drayage and regional-haul applications, known as the Heavy-Duty Fuel Cell Powertrain Commercialization Roadmap Project. This project was managed by the South Coast Air Quality Management District (SCAQMD). Key partners in this project and their roles are described in Table 1.

Table 1. Project Team

Logo	Organization	Description and Role
CALSTART	CALSTART	CALSTART, North America's leading advanced transportation technologies consortium, is a member-supported nonprofit organization of more than 300 organizations, fleets, and agencies worldwide dedicated to supporting the growth of the clean transportation industry. CALSTART's primary responsibility for this project was to develop a fuel cell technology commercialization roadmap.
SoCalGas.	Southern California Gas Company	Southern California Gas Company (SoCal Gas) is a utility company that is a subsidiary of Sempra Energy. Providing natural gas to the Los Angeles and Southern California regions, SoCal Gas is also an early pioneer in the hydrogen economy. SoCal Gas's primary responsibility was to support a fuel cell technology commercialization roadmap.
Cummins	Cummins Electrified Power NA Inc.	Cummins Electrified Power NA Inc. (Cummins) designs, manufactures, and distributes engines. Cummins has historically produced diesel and natural gas-powered engines but has become a major player in the fuel cell market. Cummins received grant funding under grant agreement ARV-16-025 to deploy and demonstrate four Class 8 FCETs.

To support this project, this report was developed to identify and propose the action items and policies needed to overcome barriers and provide a roadmap to commercialization for FCET technology. It is divided into the FCET Commercialization Roadmap and the Hydrogen Infrastructure Roadmap. These two roadmaps provide specific recommendations for deploying FCETs and hydrogen infrastructure, respectively. FCETs and hydrogen infrastructure are intrinsically linked, so both roadmaps must be implemented to advance the FCET industry.

FCET Market Opportunity

Combating the climate crisis requires decarbonization of the goods movement industry, and FCETs will play a significant role in electrifying freight. Estimating the opportunity for Class 8 FCET sales in California can help original equipment manufacturers (OEMs), fleets, and governments evaluate the future size of the FCET market both within the state and nationwide.

CALSTART projected the size of California's FCET market through 2045 by analyzing the state's regulatory environment. ZETs are more expensive than traditional Class 8 trucks. As a result, it is assumed that most fleets will not purchase ZETs in the absence of a mandate.[9] The proposed Advanced Clean Fleets (ACF) regulation would require certain fleets to adopt ZETs,[10] so this analysis assumed that these fleets attain minimal compliance. The California Air Resources Board (CARB) also published data on the number of trucks subject to the ACF regulation. This number was therefore assumed to grow in proportion with increases in freight volume. Furthermore, data from Freight Analysis Framework 4 (FAF4)[11] was used to calculate the future size of the Class 8 truck market. ACF regulation compliance targets were then applied to estimate the future size of the ZET market. As shown in Figure 1,[12] a low-uptake scenario would result in projected cumulative sales of 133,458 Class 8 FCETs by 2045. A high-uptake scenario, in which FCETs gain a monopoly on

[9] There may be some exceptions to this assumption. Since CARB funding cannot be used for ACF compliance, this could incentivize fleets to make early FCET purchases. Early purchases would allow fleets to take advantage of CARB-funded vehicle incentive programs before they are required to comply with ACF and lose access to this funding. This could induce fleets to adopt FCETs ahead of their compliance schedule.

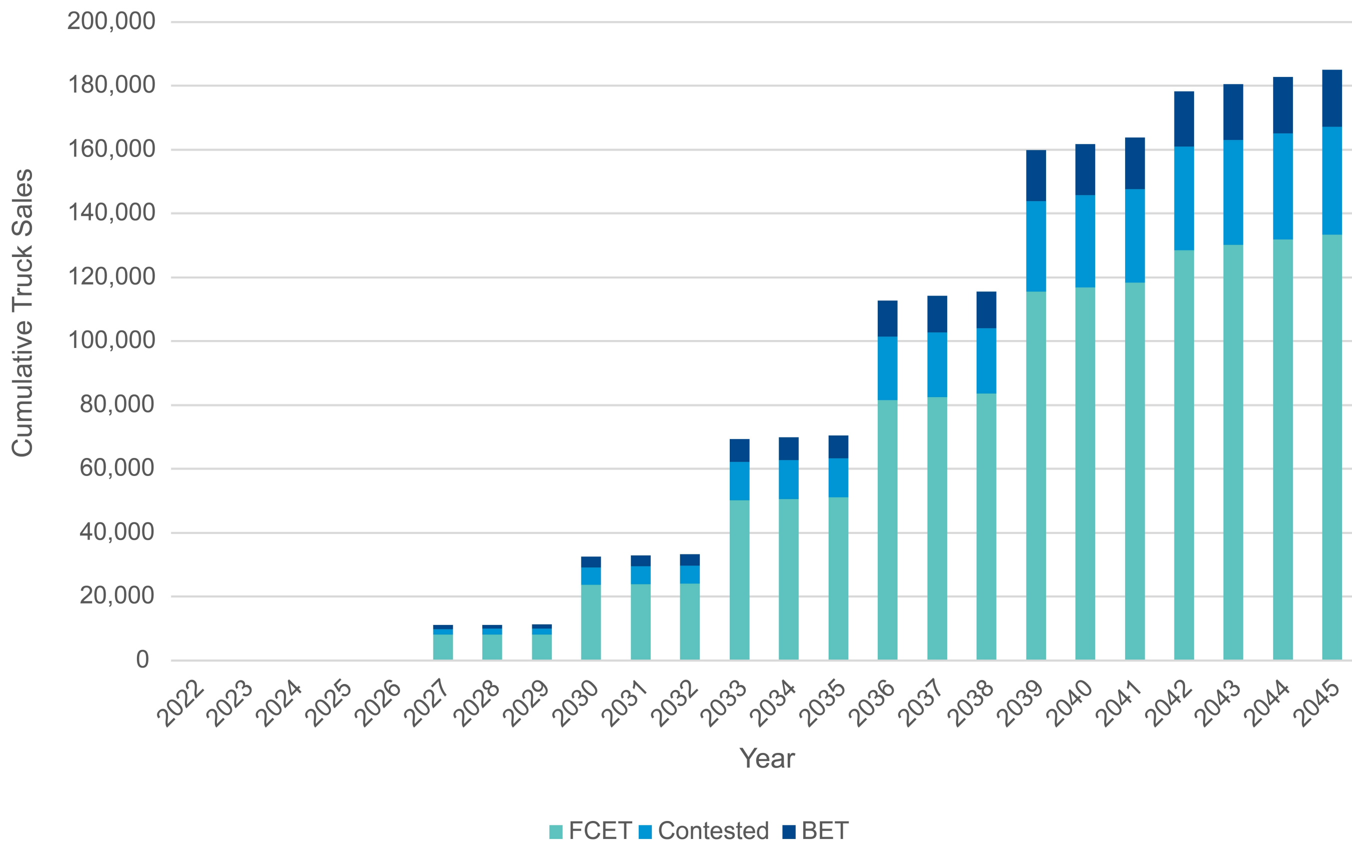
[10] The ACF regulation applies only to certain fleets, including state and municipal government fleets, federal fleets, and larger fleets with 50 or more trucks under their control.

[11] FAF4 provides a comprehensive picture of ton-miles of goods transported by truck in California. A ton-mile equals one ton traveling one mile. To view FAF4 data, visit https://www.bts.gov/faf/faf4.

[12] See **Appendix A. FCET Market Opportunity Research Methodology** for additional detail on data sources and the methodology used to develop Figure 1.

the FCET dominant sector and the entire contested sector, would result in projected cumulative sales of 167,255 Class 8 FCETs by 2045.

Figure 1. Class 8 FCET Cumulative Projected Sales in California



The potential Class 8 FCET sales within the larger ZET market were estimated using specific use cases for both BETs and FCETs, as well as the assumption that fleets will aim to use the cheapest technology that can achieve a 1-to-1 replacement with diesel trucks. BETs are expected to dominate in use cases where the vehicle travels 100 miles or less per day, while FCETs are expected to prevail in use cases where the vehicle travels more than 300 miles per day. As such, this analysis assumed that BETs would dominate the market in some use cases, FCETs would dominate in others, and the two technologies would compete in still additional cases. The amount of contested market share captured by BETs and FCETs will be determined by several factors, including but not limited to those listed in Table 2.

Table 2. Barriers to ZET Adoption

Barriers	Description
Vehicle price	The capital cost of the vehicle is a major factor in a fleet's decision to adopt BETs or FCETs. As of 2022, a new Class 8 BET sells for approximately $450,000 compared to $700,000 for a new Class 8 FCET.[13] Upfront costs for both vehicle types are expected to fall over the coming years; however, the rate at which prices for each technology decreases will impact vehicle uptake.
Price of hydrogen	The current high price of hydrogen significantly impacts FCETs' total cost of ownership (TCO) and fleets' willingness to adopt this technology. The price of hydrogen is expected to drop due to economies of scale and several programs aimed specifically at decreasing the cost of hydrogen.
Hydrogen fueling network	The availability of HD hydrogen fueling stations will be a major constraint to the uptake of FCETs. As this writing, there are only four HD hydrogen stations in California. New incentive programs like the Energy Infrastructure Incentives for Zero-Emission (EnergIIZE) Commercial Vehicles Project will help accelerate the rollout of a hydrogen fueling network.
Fast charging	The speed at which a vehicle can recharge or refuel is an important factor. If a vehicle is recharging or refueling, it may be limited to fewer shifts per day than a diesel vehicle. As a result, vehicle downtime due to fueling is a factor that fleets consider. The salience of this factor depends on duty cycle. Trucks that reliably have operational breaks during the day can potentially charge or fuel during idle time. However, this factor is extremely important for trucks that are in continuous operation throughout the day. One advantage FCETs currently have over BETs is that hydrogen refueling is faster than charging, and FCETs have a greater range than BETs from one fueling session [Al-Alawi, 2022a]. However, the industry has been working on developing faster charging solutions with CARB programs like Research Hub for Electric Technologies in Truck Applications (RHETTA). If faster charging solutions are developed, it can help mitigate range disadvantage for BETs.

[13] Based on prices of BETs and FCETs that were funded under CEC's GFO-20-606 solicitation. CALSTART obtained BET and FCET pricing data from this solicitation from a public records request. The price of BETs and FCETs was calculated by taking the average price of BETs and FCETs funded under this solicitation. For more information about GFO-20-606, visit https://www.grants.ca.gov/grants/gfo-20-606-zero-emission-drayage-truck-and-infrastructure-pilot-project/.

In most cases, it is not feasible to have a mixed fleet with both Class 8 BETs and FCETs. Installing charging or fueling infrastructure is a major investment and often leads to fleets committing to one technology.[14] The high price and long lifetime of charging and fueling infrastructure will likely lock fleets into either BET or FCET operations. As a result, early developments in the factors above can have dramatic long-term implications on the market share that each technology captures.

The uptake of BETs and FCETs over the coming decade may determine their market share of truck sales for decades to come. While FCETs have clear operational advantages including quick refueling and a longer range than BETs, FCETs are less commercially available and have several barriers to address. The next section discusses the four stages of commercialization that FCETs must go through and describes clear achievements that will dictate the transition from market introduction to maturity.

Commercialization Stages

The FCET market will need support to transition from an early-stage market to maturity. This market transformation is expected to take place in four phases. Each phase represents a step toward commercial maturity and is defined based on the level of external (mainly government) support that the market requires and the extent to which the market benefits from economies of scale.[15]

1. **Introduction Phase:** Phase 1 is marked by small-scale demonstrations, from one truck to a maximum of 20. In this phase, the HD hydrogen fueling network is in its infancy and is not yet developed. OEMs will likely have to provide hydrogen for the demonstration trucks or install temporary fueling stations. The FCET market is currently in this phase, with only small demonstrations and four permanent HD stations in California. The 2019–2021 Zero- and Near Zero-Emission Freight Facilities Project (ZANZEFF) provided funding for the Zero Emission Freight "Shore-to-Store" Project, which took place at the Port of Long Beach and funded 10 FCETs and two HD hydrogen stations. This project cost $41.1 million in state funding and $41.5 million in match funding [Port of Los Angeles, n.d.].
2. **Development Phase:** Phase 2 is marked by medium-scale demonstrations of more than 20 trucks. During Phase 2, hydrogen infrastructure is initiated with government

[14] A possible exception could be a situation where public charging/refueling is readily available or if a large fleet has both a local delivery fleet and long-haul trucking fleet.

[15] This framework was modified from the commercialization plan developed in CALSTART's Near Zero-Emission Heavy Duty Truck Commercialization Study [Gallo, 2013].

assistance and funding. CEC awarded funding to develop five HD fueling stations under GFO-19-602 [CEC, 2020]. These stations will come online in 2023 and 2024, representing the start of the development of a hydrogen fueling network with government assistance. The NorCAL Zero-Emission Regional Drayage Project was also started with funding from CEC and CARB [CEC, 2020a]. This project funded a demonstration of 30 Hyundai FCETs at the Port of Oakland as well as one HD fueling station. CEC and CARB provided $55 million in funding. This project will begin in 2023; Phase 2 is therefore expected to begin in 2023. It is important to note that a single Phase 2 project is not sufficient for progressing to more advanced commercialization phases. Further investment in medium-scale demonstrations and hydrogen infrastructure is required to advance to the next phase.

3. **Growth Phase:** Phase 3 will begin when customers start purchasing FCETs without government demonstration funding (though incentives/subsidies will likely still be available). FCET market growth will begin in applications that are easiest to adopt FCETs, and since the hydrogen fueling network is not yet complete, this mainly restricts FCETs to regional-haul and return-to-base operations. Most deployments are near ports and concentrations of warehouses (Port of Long Beach/Inland Empire Corridor, Port of San Diego, Port of Oakland/San Joaquin Valley Corridor). The hydrogen fueling network serves as a constraint to growth. To address this issue, hydrogen providers need to begin investing in retail fueling independently without government support. CALSTART's interviews with hydrogen producers and retail station developers for this project indicate that 500–900 Class 8 FCETs in operation would demand enough hydrogen to induce hydrogen providers to invest in retail stations. Some fleets might also deploy onsite hydrogen infrastructure. During the Growth Phase, this volume of FCET sales will allow OEMs to begin to take advantage of economies of scale. As a result, it is assumed that the price of hydrogen and the cost of the vehicles will experience substantial reductions.
4. **Mature Phase:** In Phase 4, FCETs will be used in all feasible applications including long-haul applications. FCETs will expand beyond port/warehouse concentrated areas, and the emergence of a statewide hydrogen fueling network will allow FCETs to operate in long-haul operations. This phase will see the development of hydrogen fueling corridors (possibilities include Los Angeles-Las Vegas, Los Angeles-Arizona, and Central Valley (I-5/I-99)). Long-haul FCETs will be supported by fueling infrastructure deployed in neighboring states. Truck stops can sell hydrogen only if it achieves the same rate of return as other fuels, so truck stops deploying hydrogen fueling would be an indicator that the market has achieved maturity. The price of

hydrogen and the cost of FCETs will need to reach (or approach) parity with diesel for the market to reach maturity.

The FCET market is currently transitioning from Phase 1 (Introduction) to Phase 2 (Development). The start of the NorCAL Zero-Emission Regional Drayage Project in 2023 will officially mark the beginning of Phase 2. This roadmap is based on the market achieving economies of scale and government support for the industry being implemented. These factors are more important for driving commercialization than time. Therefore, this roadmap does not provide projections for when the market will transition to Phase 3 (Growth) or Phase 4 (Maturity).

Societal Benefits for Californians

Commercializing and deploying Class 8 FCETs will require a significant amount of government funding, policy support, and industry action, but these investments to advance commercialization will provide significant environmental and economic benefits to California. With zero tailpipe emissions, and especially when hydrogen is produced from a renewable source, FCETs will help to combat climate change, improve air quality, and promote human health. In addition, FCETs offer economic opportunities for Californians, as described in more detail below.

Emissions Reductions

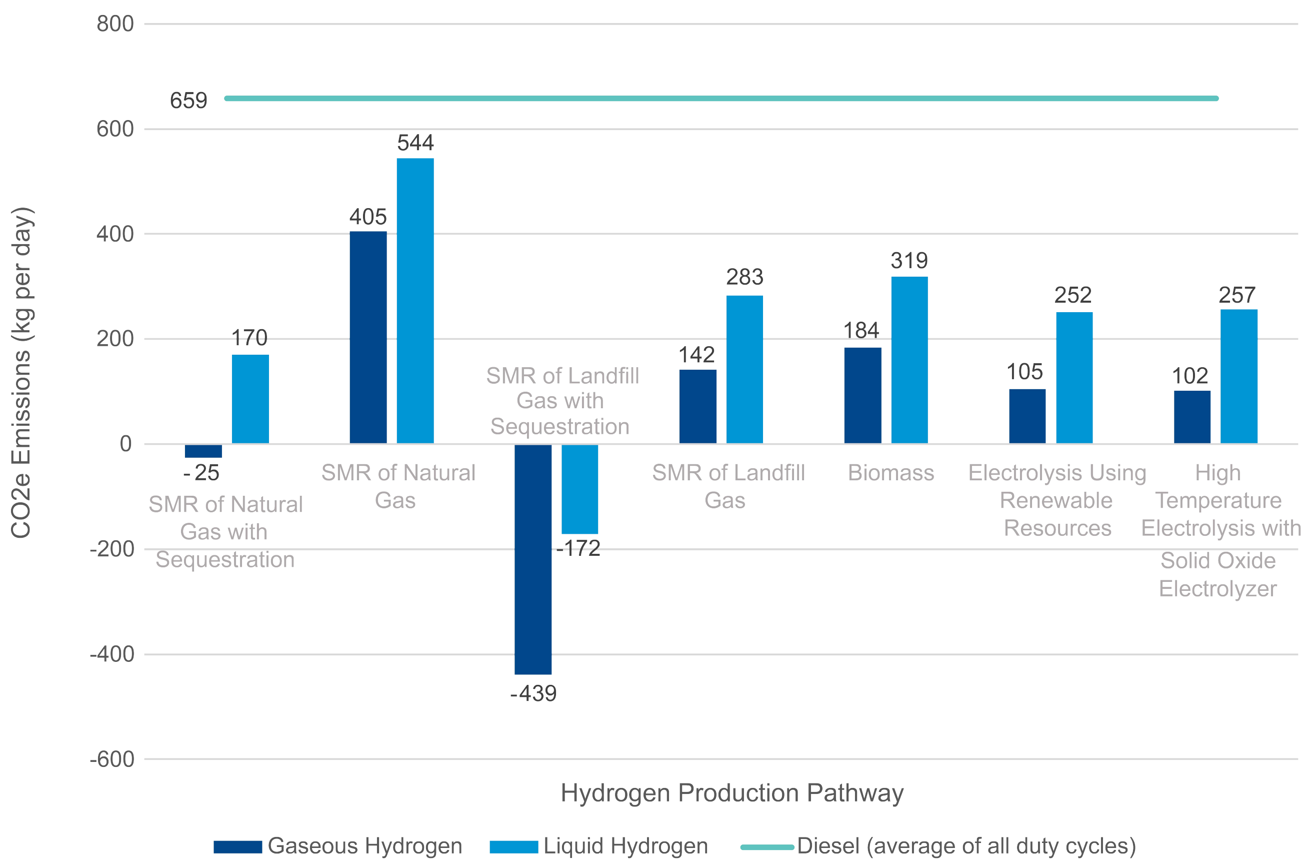
Regular diesel-powered Class 8 trucks produce a large amount of pollution, including GHG emissions (which drive climate change) and criteria pollutants like NOx, carbon monoxide (CO), and particulate matter (PM). These criteria pollutants reduce air quality and harm human health. Class 8 trucks are concentrated along certain corridors and near ports, meaning these areas receive a disproportionate amount of pollution and have much worse air quality than other parts of the state. As a result, these areas experience a higher incidence of respiratory and general health problems. Many of these impacted areas also suffer from higher levels of poverty [Di Filippo, 2019].

FCETs can help address these problems by reducing emissions. CALSTART compared GHG emissions from Class 8 diesel trucks to Class 8 FCETs, investigating several types of duty cycles for trucks serving the Ports of Los Angeles and Long Beach, the Port of Oakland, all other Californian ports (Other Ports), and Class 8 trucks that do not visit ports (Non-port Class 8 Trucks). This analysis also investigated several hydrogen production pathways.[16]

[16] The methodology that was used to conduct this analysis can be found in **Appendix B. Emissions Analysis**.

Figure 2 illustrates that FCETs produce fewer life-cycle GHG emissions and can provide substantial emissions reductions. Life-cycle emissions, which account for emissions from fuel production, are included since GHG emissions contribute to climate change regardless of where they are produced.

Figure 2. Total GHG Emissions Comparison



All investigated hydrogen pathways have lower GHG emissions compared to diesel. However, the reduction in GHG emissions is highly dependent on the hydrogen production pathway. Liquid hydrogen pathways have higher GHG emissions than gaseous hydrogen pathways due to the additional energy needed for hydrogen liquification.

FCETs also reduce criteria pollutants. Since criteria pollutants have local impacts on air quality, this analysis focused on tailpipe emissions. FCETs do not produce any tailpipe emissions, consequently eliminating the NOx and CO pollutants Class 8 diesel trucks emit into communities. In addition, FCETs provide substantial reductions in PM emissions (though FCETs still produce PM due to brake and tire wear). Figure 3 and Figure 4 below display the reductions in PM emissions that FCETs can provide. The methodology for these calculations can be found in **Appendix B. Emissions Analysis**.

Figure 3. PM10 Emissions Reduction from FCET Deployment

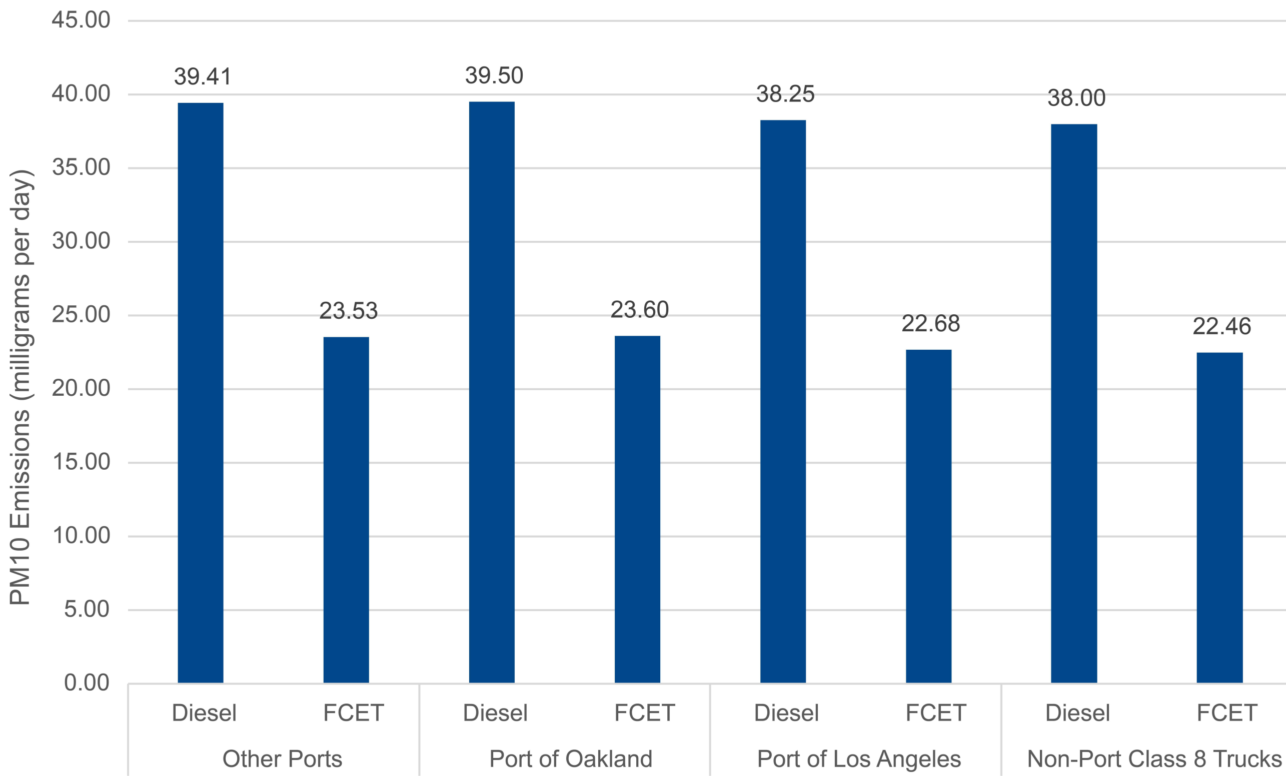
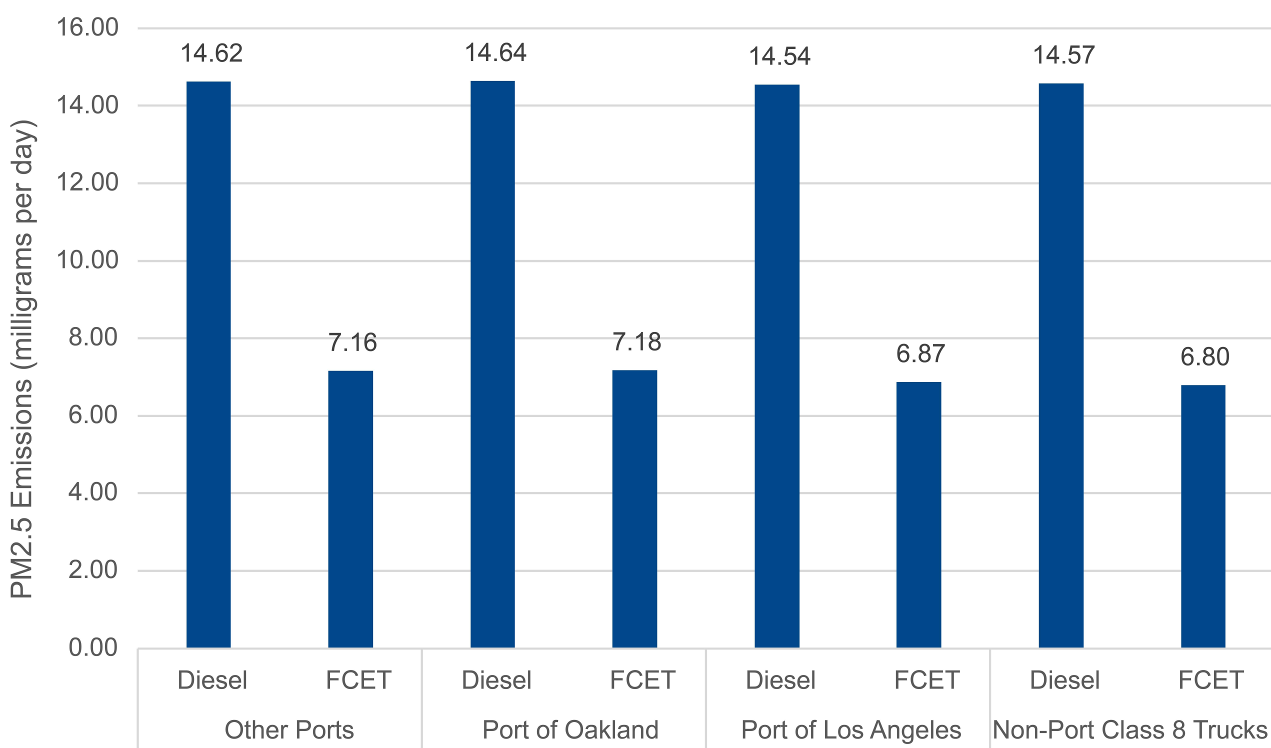


Figure 4. PM2.5 Emissions Reduction from FCET Deployment



Employment and Economic Benefits

Deploying FCETs also provides an opportunity to create jobs, spur economic growth, and upskill the existing workforce. Class 8 trucks must be maintained and repaired over the course of their life cycle, and this job function is currently carried out by maintenance technicians. Diesel mechanics are maintenance technicians that work on diesel trucks. The number of maintenance technician jobs is correlated to freight volumes. In 2018, there were 24,600 maintenance technicians in California. By 2028, the net change in this number is expected to increase by 7.7%, equating to a net gain of approximately 1,900 technician jobs [Employment Development Department, 2022].

As of 2022, a diesel mechanic's median salary was $62,564 and the 75th percentile salary was $76,875 [Employment Development Department, 2022]. After being trained in fuel cell technology, these technicians will likely be able to command a wage premium as their job requires a more technical skillset. These jobs do not require a four-year college degree or likely a significant amount of student debt to start a career in this field. Many technicians receive training at a community college or trade school or from a vehicle manufacturer. These positions are critical to the FCET industry and goods movement as fleets begin to electrify, especially given the current lack of workforce development. (See **Address Other Enabling Factors** section under the FCET Commercialization Roadmap for further discussion and actions items to address this barrier.)

Deploying Class 8 FCETs will also have wider economic impacts beyond creating jobs for maintenance technicians. A report from the Fuel Cell & Hydrogen Energy Association estimated the economic impacts of transitioning to a hydrogen economy. This study examined the use of hydrogen in the U.S. transportation, residential and commercial building, industrial, and power generation sectors. The study found that the hydrogen economy in the United States could generate $750 billion in annual revenue by 2050 [Fuel Cell & Hydrogen Energy Association, 2020]. Transportation was responsible for 42.9% of hydrogen demand. Assuming that each sector contributes a proportionate share of economic activity, the transportation sector is expected to generate $321 billion in annual revenue in the United States by 2050.

States will be competing to capture the economic benefits of the hydrogen economy. California is well positioned to capture market share because it has served as an early adopter of zero-emission vehicles and FCETs. California has capitalized on its competitive advantage as several fuel cell companies have invested in the state. In 2021, Cummins opened its Hydrogen Fuel Cell Powertrain Integration Center in West Sacramento to conduct research and development on fuel cell powertrains [Cummins, 2021]. In addition, multiple hydrogen producers and retail fueling station developers have and will continue to invest in the state.

These investments will create additional jobs in California beyond maintenance technicians. Jobs will also be created in vehicle engineering and manufacturing and in the supply chain for hydrogen infrastructure and production equipment. CALSTART quantified this job creation potential using CARB's Job Co-benefit Modelling Tool.[17] CALSTART used this tool to estimate the number of jobs that will be created for every $1 million of investment (Table 3).

Table 3. Job Creation from Hydrogen Economy Investment

Type of Investment	Jobs Created (Per $1 million Invested)
Fuel Production Facilities	13.7
Procurement, Repower, or Retrofit of HD Trucks and Buses	9.1
Research and Development	9.1

[17] To access CARB's Job Co-benefit Modeling Tool or to learn more, visit https://ww2.arb.ca.gov/sites/default/files/auction-proceeds/final_jobs_userguide.pdf.

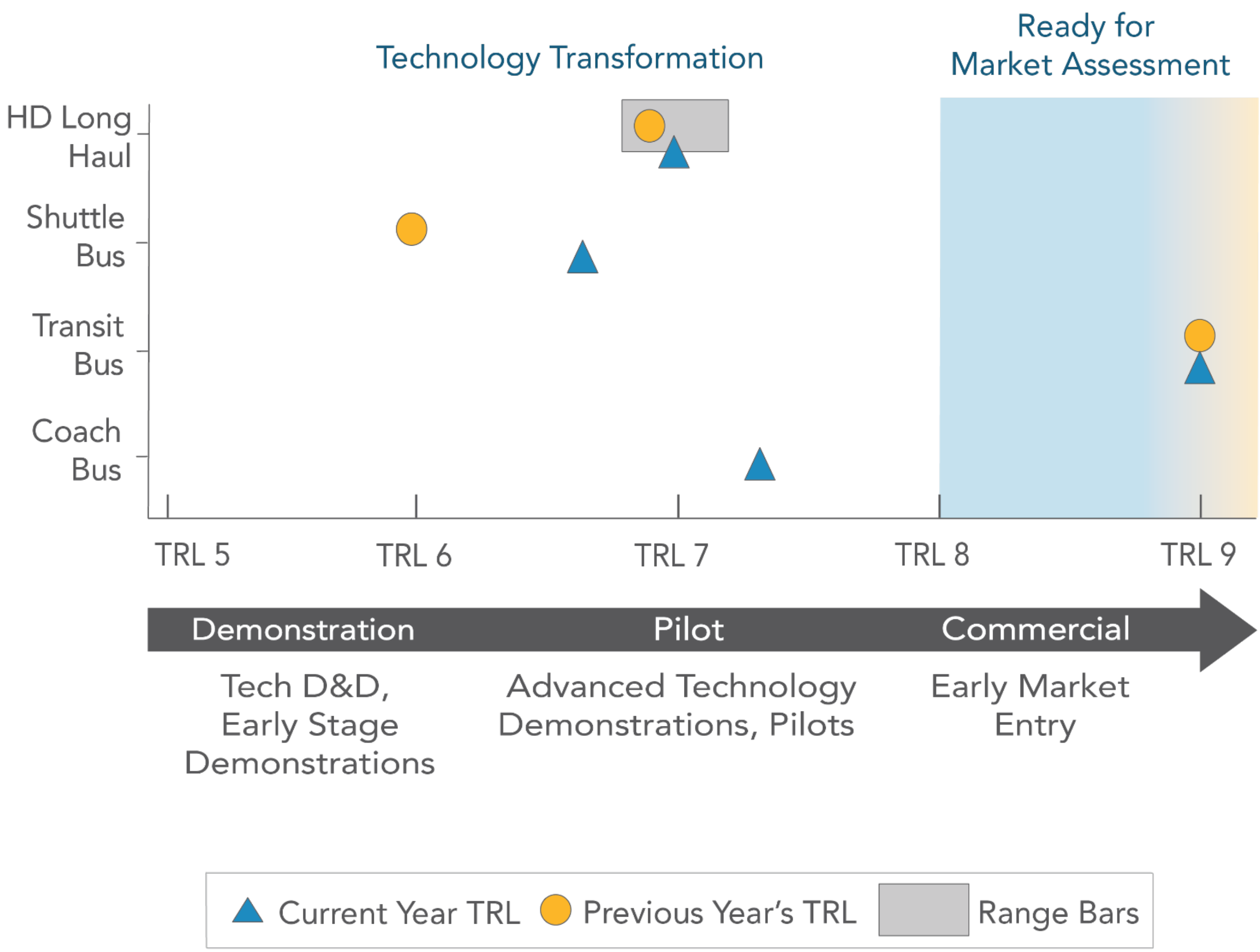
II. FCET Commercialization Roadmap

Currently the vast majority of over-the-road freight movement in California is transported by diesel-powered Class 8 trucks. Class 8 diesel trucks are responsible for a disproportionate amount of GHG and criteria emissions, which drives climate change and harms air quality. The State of California aims to address these environmental problems by deploying ZETs, with the ultimate objective of replacing the current diesel-powered fleet with zero-emission technology.

FCETs have emerged as a zero-emission alternative to conventional Class 8 trucks. While these vehicles are in earlier stages of technological maturity compared to other zero-emission technologies, the capabilities and performance of Class 8 FCETs has significantly improved over time. Technological maturity can be measured by metrics like technology readiness levels (TRLs). Technologies typically go through several iterations of development before becoming a fully commercialized product. New products start off as a technology concept, which is then applied, validated in laboratory settings, validated in experimental settings, developed into a prototype, and demonstrated before becoming a fully commercialized product. TRL analyses aim to quantify a product's progression through this process. TRLs use a scale from one to nine, with nine being a fully commercialized technology.

Seen in Figure 5, as of 2022, HD long-haul FCETs have a TRL of seven and are now considered to be in the Advanced Technology Pilot and Demonstrations phase of technological development [CARB, 2022a]. FCETs will still need to undergo additional development to be a commercial technology, which requires a TRL score of eight or higher.

Figure 5. On-Road Fuel Cell Electric Vehicles Technology Status Snapshot [CARB, 2022a]



While Class 8 FCETs will need further technology development for early market entry, this development does not necessarily equate to commercial readiness. There are other non-technology factors that need to be addressed to prepare the market for FCET adoption. For this reason, CALSTART conducted research into the FCET market to understand the drivers and barriers to commercialization, which are presented in this first roadmap. CALSTART completed a literature review of secondary sources from industry, U.S. governmental agencies, and academia, as well as interviewed truck fleets to understand this market.[18]

Concerted action must be taken to advance FCET technology and to prepare the market for FCET adoption. Action will also need to be taken to address non-technological barriers

[18] See **Appendix I. Interview Methodology** for details about these interviews.

to FCET adoption. CALSTART has determined three broad recommendations for state and federal government, financers, OEMs, and fleets to help accelerate Class 8 FCET commercialization:

1. Reduce FCET upfront costs and TCO.
2. Promote commercial readiness and user acceptance of FCETs.
3. Address other enabling factors, such as weight penalty, lack of specialized workforce, and manufacturing.

The following three sections break down each recommendation into one or more action items, as well as responsible entities and estimated cost to achieve each goal (when applicable). The resulting roadmap will help accelerate the market to Phase 4, in which FCETs will be used in long-haul and all other feasible applications.

Reduce Upfront Costs and TCO

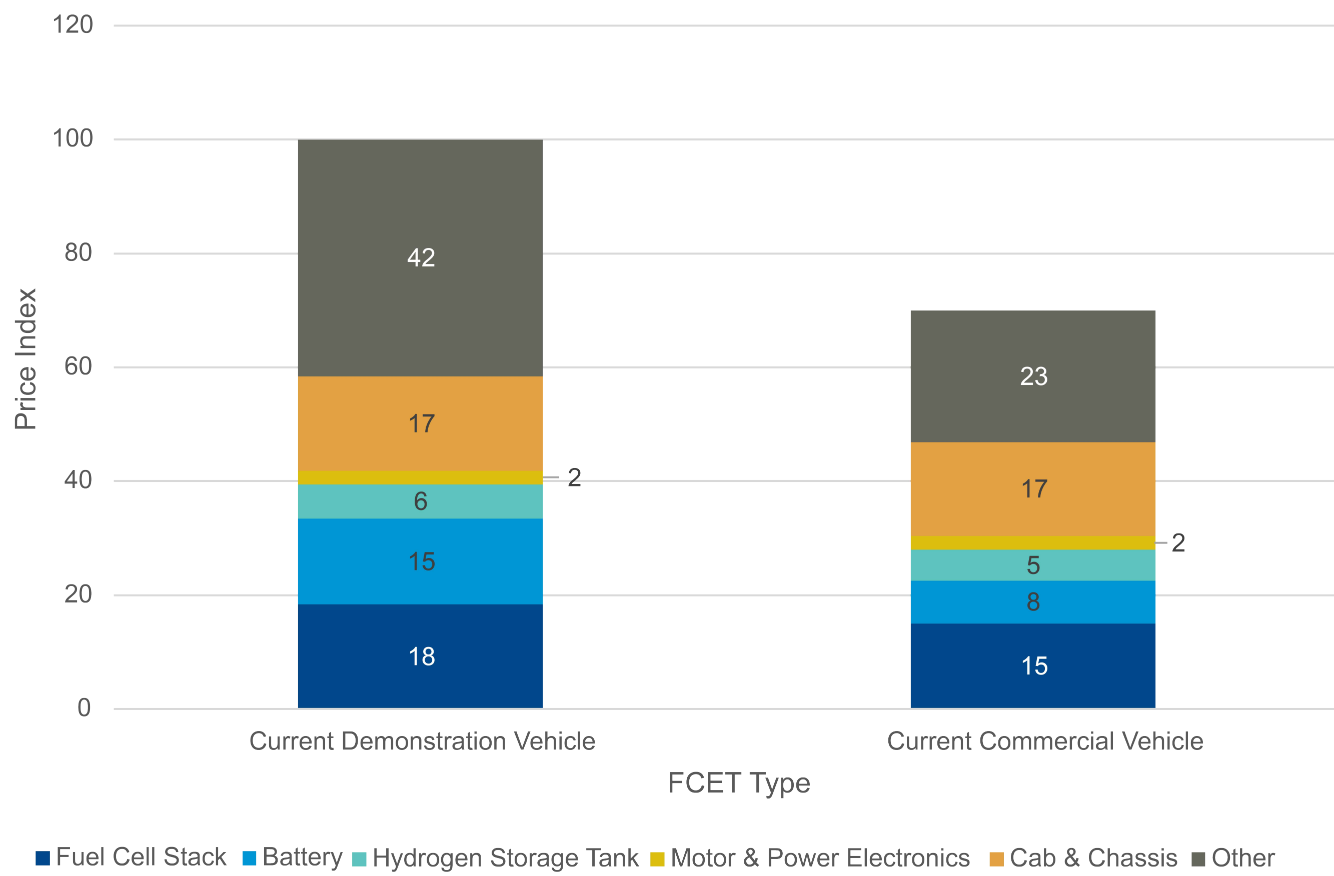
During interviews, fleet owners frequently raised their concerns about the high upfront cost and TCO for FCETs over the course of this project. Given that these vehicles have yet to complete an entire life cycle on the road, some of the associated costs, such as maintenance and midlife repairs, remain unknown. This uncertainty with respect to TCO can pose a barrier to technology adoption and hinder the development of FCET business models. Since TCO for Class 8 FCETs is currently higher than for diesel trucks, this price disparity must be resolved to advance the industry.

Vehicle Costs and Component Cost Contributions

FCETs are a relatively new technology and were only recently commercialized, so pricing for these vehicles is often scarce or difficult for fleets to locate. CALSTART collected data on FCET pricing during this project, determining that it is highly variable between OEMs that are in different stages of the commercialization process. Some OEMs have a commercialized product available for sale and that fleets can order, but other OEMs have a demonstration vehicle in the earlier stages of development that only select fleets who have agreed to host a small number of vehicles for testing can deploy. Demonstration vehicles are not a finalized product and fleets are unable to order them. Commercialized Class 8 FCETs tend to be cheaper than demonstration vehicles: one to two demonstration vehicles are produced at a time and therefore cannot take advantage of economies of scale. Commercial FCETs are produced in higher quantities, though marginally, and can begin to benefit from scale.

Based on CALSTART's research, a demonstration Class 8 FCET can cost approximately $1,000,000. Commercial FCETs are significantly less expensive than a demonstration vehicle, but commercial FCETs are still much more expensive than diesel trucks. Based on data collected from industry, the average cost of a commercial Class 8 FCET is approximately $700,000, a significant premium over a new diesel truck priced at approximately $150,000. CALSTART examined the cost breakdown for the major components of FCETs and their individual contributions to the total cost of the vehicle for both demonstration and commercial FCETs (Figure 6).[19]

Figure 6. Class 8 FCET Component Cost Breakdown



[19] The methodology for this figure can be found in **Appendix C. Class 8 FCET Costs**.

The U.S. Department of Energy (DOE) recognizes that FCET component costs must decrease in order for these vehicles to become financially viable for fleets. In 2019, DOE released performance targets for Class 8 FCETs that call specifically for reductions in fuel cell system cost and a decrease in hydrogen storage cost, among other technical targets to accelerate commercialization [DOE, 2019]:

- 2030 interim goals:
    - Fuel cell systems cost $80 per kilowatt (kW).
    - Hydrogen storage systems cost $9 per kilowatt-hour (kWh), or $300 per kilogram (kg) of hydrogen stored.
- 2050 goals:
    - Fuel cell systems cost $60 per kW.
    - Hydrogen storage systems cost $8 per kWh, or $266 per kg of hydrogen stored.

TCO Sensitivities

TCO measures the total cost of the vehicle over its lifetime, taking into account factors such as vehicle cost, the federal excise tax for trucks, maintenance costs, fuel costs, residual values, and incentive funding. While the upfront costs of the vehicles are known, many other TCO factors cannot be determined until more FCETs begin to reach the end of their life cycle.

Since there have been few FCET demonstrations, maintenance cost analyses are not complete. Furthermore, any completed demonstrations have been short-term. Since major repairs are typically not required until later in the life of the vehicle, these demonstrations likely do not reflect total maintenance costs.[20] For instance, midlife repairs are a major liability for diesel trucks. During its lifetime, a truck's engine will degrade to the point where it must be rebuilt or refurbished, an additional cost that many fleets will try to avoid by selling the vehicle. While FCETs do not have a traditional internal combustion engine, fuel cells do have a finite lifespan, and it is likely that the fuel cell will need to be refurbished or replaced. The costs and frequency of this occurrence is currently unknown.

Another key component of TCO is residual value, also known as salvage value. At the end of the life of a truck, fleet owners will usually sell it. Most fleets keep their trucks for five to seven years. According to data from CARB, after this time, a Class 8 diesel truck has a

[20] This statement is also true for BET demonstrations.

residual value of 25%–35% [CARB, 2020]. It is still unclear whether an FCET will have this level of, or any, residual value at the end of its life.

Economies of Scale

Class 8 FCETs are less commercialized than both BETs and diesel trucks. Since fewer FCETs have been manufactured and deployed, each FCET unit is more expensive. As shown in Figure 6 and discussed above, the fuel cell and the onboard hydrogen storage tank are the most expensive propulsion components on FCETs. These components are currently produced at low volumes and are therefore expected to benefit from economies of scale as production volumes increase (i.e., the price of these components is expected to drop as production ramps up).

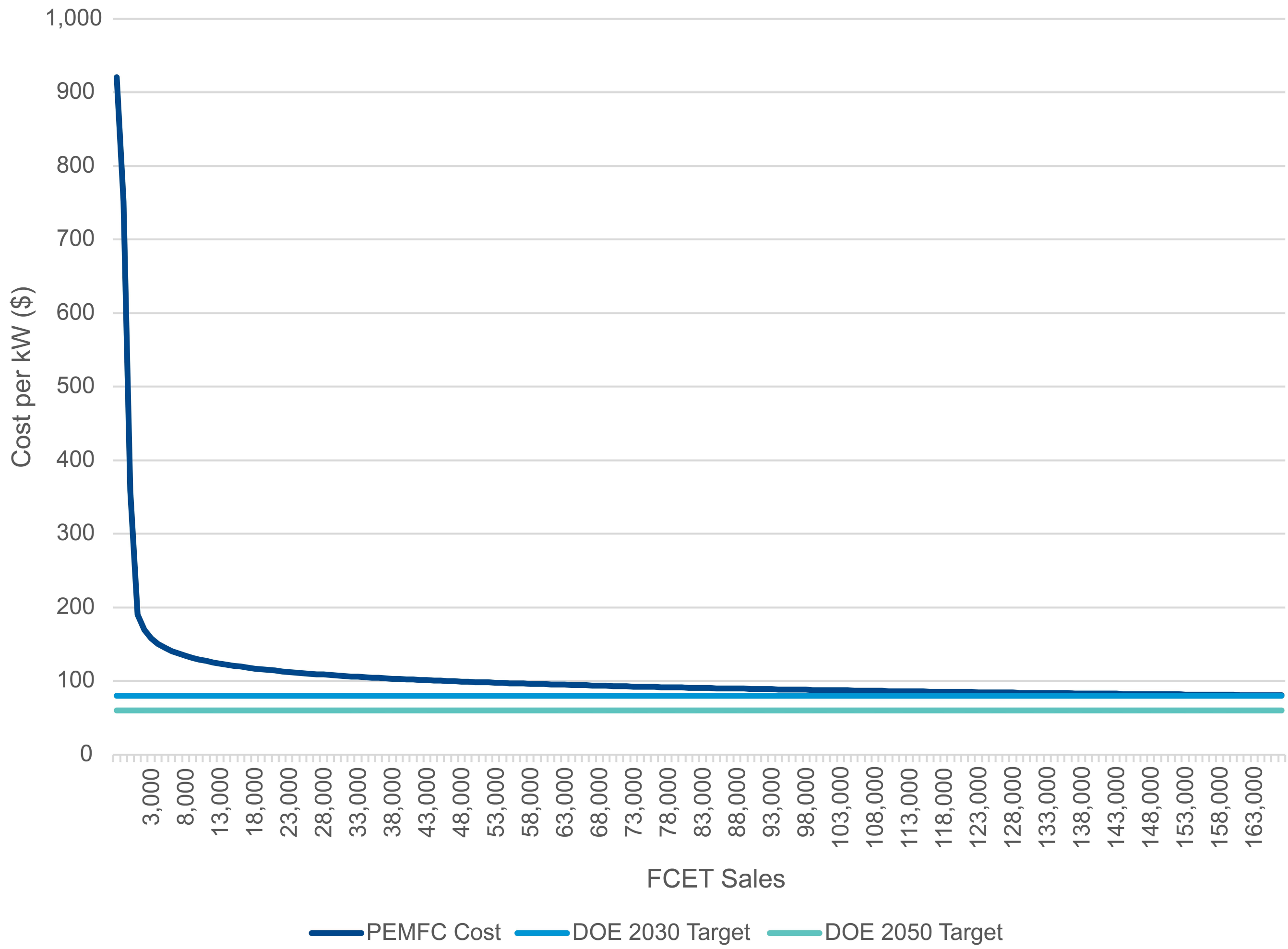
CALSTART modeled the impact of economies of scale on the price of these two components. The modelling methodology used was borrowed from a study conducted by Eleanora Ruffini and Max Wei, which used learning rates[21] to model prices changes in response to increased production volumes.[22] This methodology was used to project how the price of fuel cells and onboard hydrogen storage tanks will change as production increases.

[21] A learning rate represents the percent decrease in the price of a good that occurs when production volume doubles.

[22] See **Appendix C. Class 8 FCET Costs** for more details about this methodology.

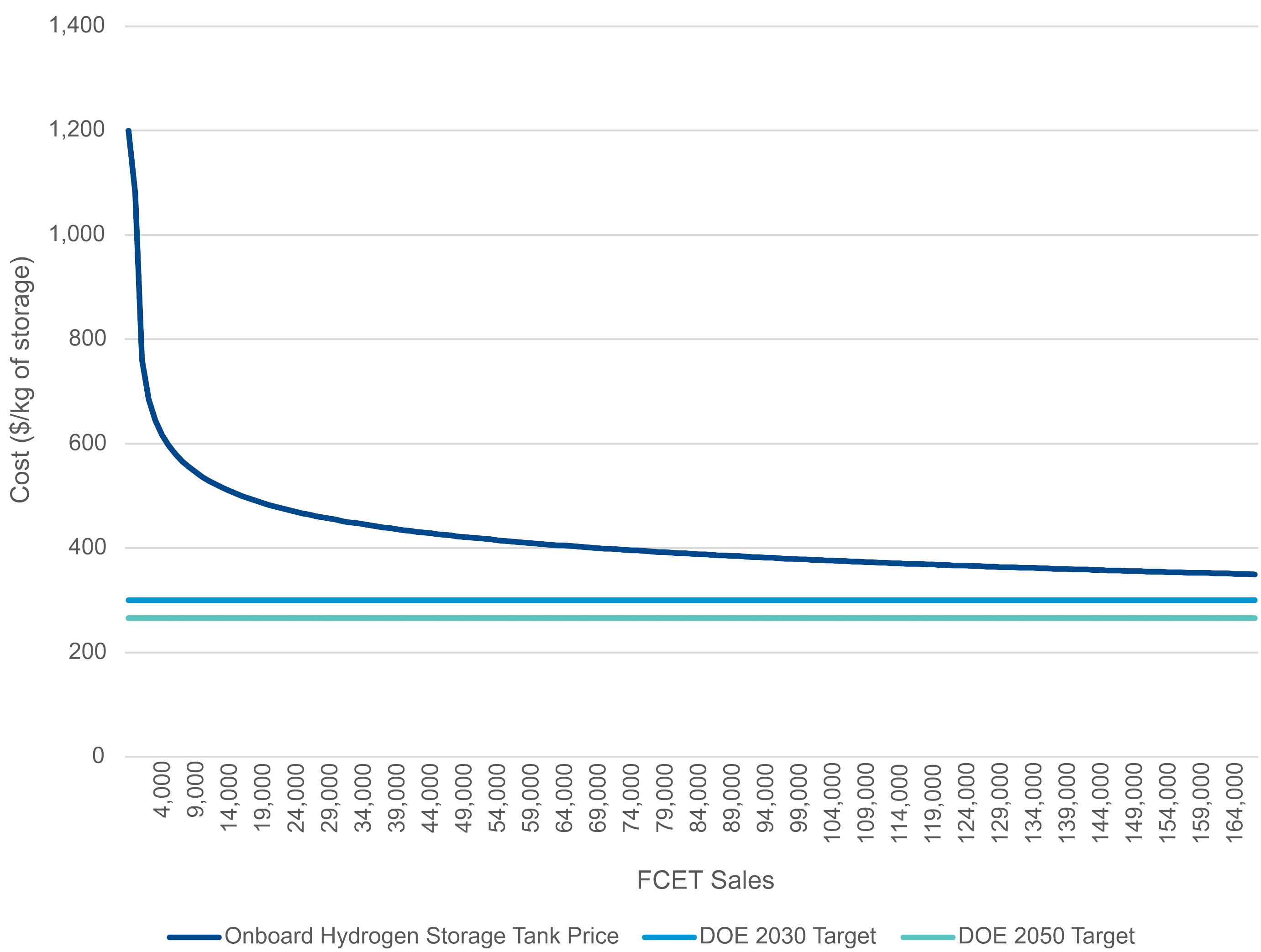
Figure 7 displays the projected price of proton membrane exchange fuel cells (PEMFCs) and how this projection compares to DOE's 2030 and 2050 cost targets. As shown below, the cost of fuel cells will decrease dramatically with economies of scale. Under this projection, the cost of PEMFCs will approach DOE's 2030 target. However, even under the most optimistic Class 8 FCET sales projections, the cost will not drop to reach DOE's 2050 target.

Figure 7. Projected PEMFC Costs



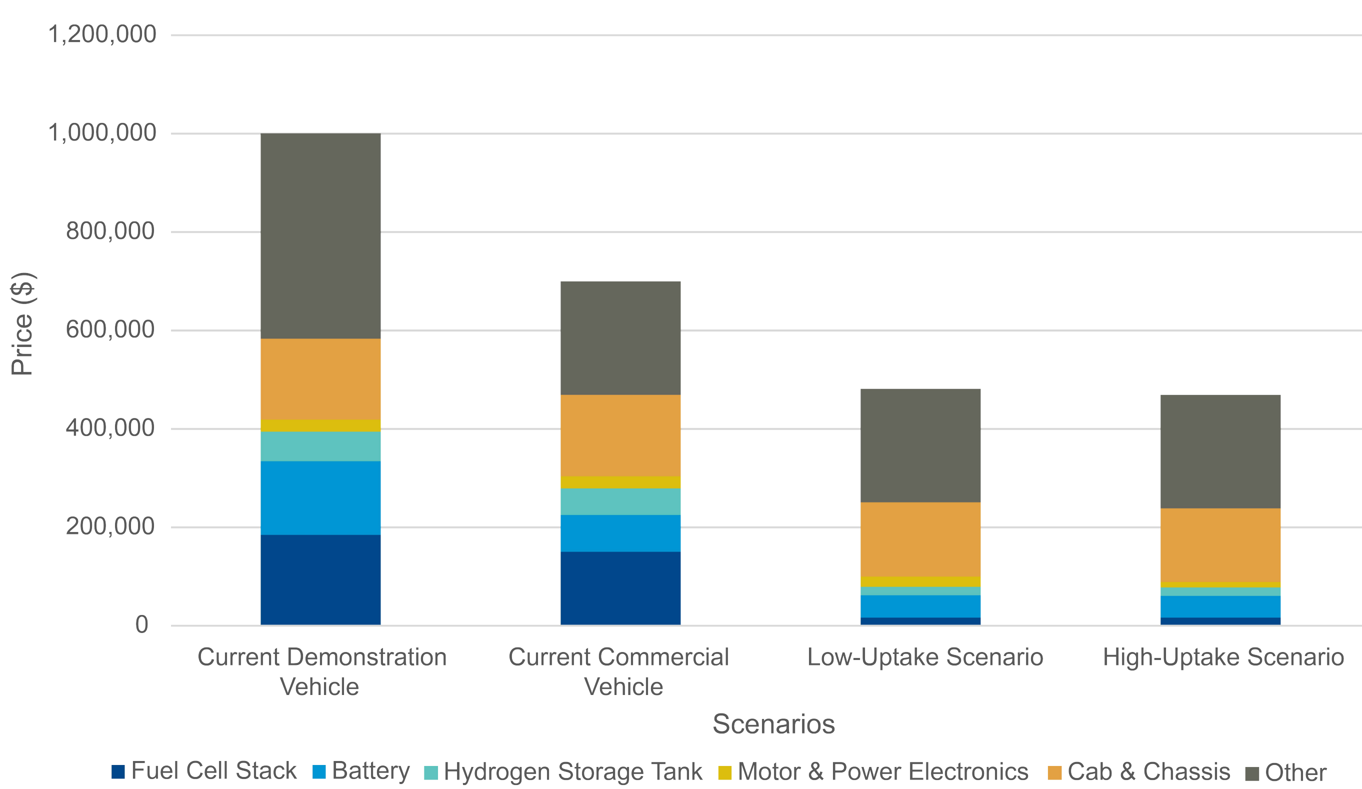
The learning rates model was also applied to onboard hydrogen storage tanks (Figure 8). According to Ruffini and Wei, the learning rate for these tanks is 10%. The cost of onboard hydrogen storage tanks will also decrease dramatically with economies of scale, but the cost will not drop to the 2030 or 2050 DOE targets even under the most optimistic Class 8 FCET sales projections.

Figure 8. Projected Onboard Hydrogen Tank Costs



Reducing the price of the two most expensive zero-emission components will benefit overall FCET prices, but other major components (i.e., battery, traction motor and power electronics, and the cab and chassis) and factors like research and development, cost of sales, and profit margin all play a significant role in determining final FCET price tags for fleet owners. CALSTART projected the future price of FCETs in Figure 9 below by modelling the prices of the major components as they reach economies of scale and comparing the impact that economies of scale will have on FCET price based on the low-uptake and high-uptake scenarios described in Figure 1. The price of the fuel cell stack, battery, and hydrogen storage tank were based on Ruffini and Wei's methodology described above. The motor and power electronics costs were modeled based on data from U.S DRIVE [U.S. DRIVE, 2017].[23]

Figure 9. Projected Class 8 FCET Vehicle Prices



There is a significant decrease in price during the transition from a demonstration vehicle to a commercialized vehicle due to standardized components and an established manufacturing process, both of which reduce the manufacturing cost. But as shown above, further decreases in FCET price can be achieved through economies of scale. More FCET sales will assist in reducing the price of these vehicle components. However, additional action must be taken to meet DOE targets and further decrease the upfront cost of FCETs.

Inflation Reduction Act

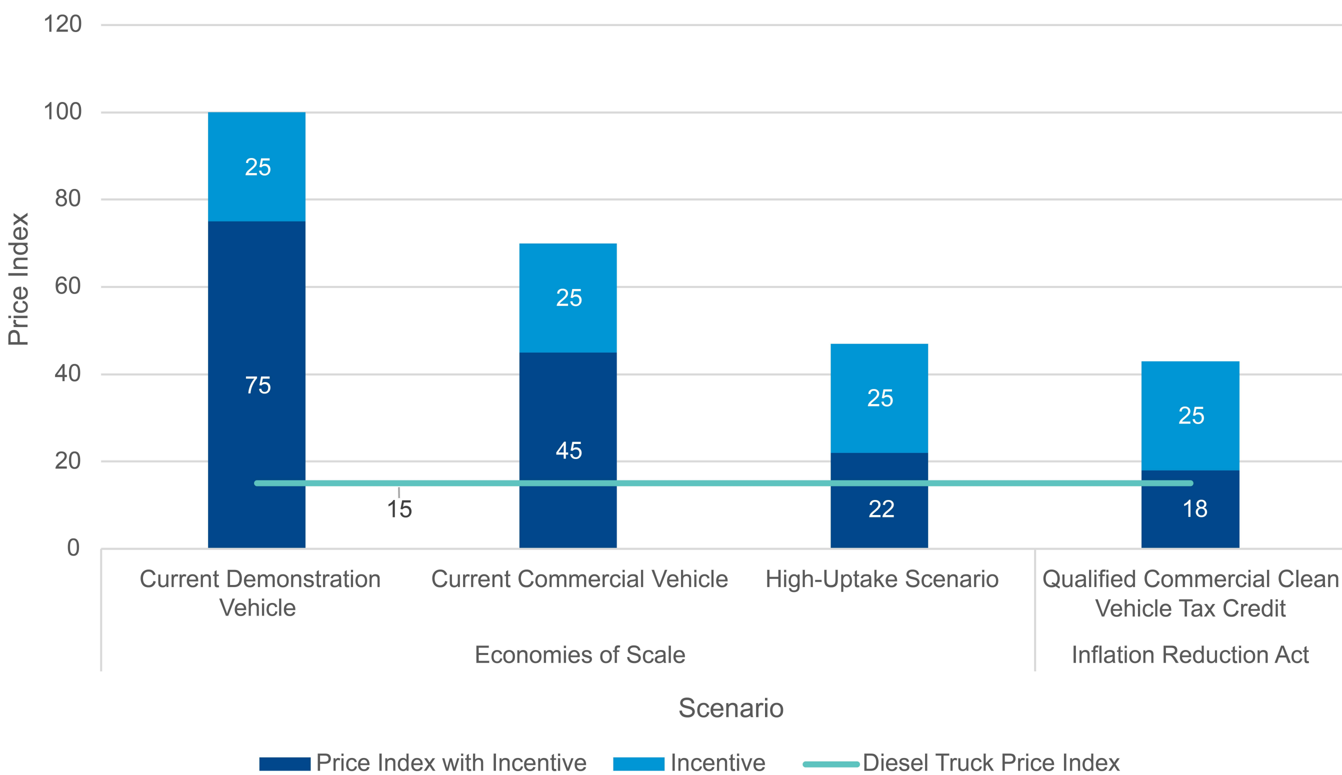
The Inflation Reduction Act was passed by the Senate and the House of Representatives on August 7, 2022, and August 12, 2022, respectively, and was later signed into law on August 16, 2022. This landmark climate bill includes provisions that will benefit FCET commercialization, including a provision that will help lower the capital costs of an FCET.

[23] See **Appendix C. Class 8 FCET Costs** for this methodology.

Section 13403 provides a tax credit for Qualified Commercial Clean Vehicles. The tax credit is equal to the lesser of 30% of the cost of the qualified commercial clean vehicle or the incremental cost. The value of the credit is capped at $40,000 for vehicles weighing more than 14,000 pounds. Given the high upfront costs of an FCET, this provision effectively creates a $40,000 tax credit for Class 8 FCETs. The vehicle must be purchased by December 31, 2032, to qualify for this credit.

Figure 10 shows the impact that the provisions in the Inflation Reduction Act are projected to have on the price of FCETs, as well as the impact of $250,000 of incentive funding per vehicle.[24] With incentive funding, the price of an FCET begins to approach parity with the price of a diesel truck.

Figure 10. Class 8 FCET Price Index



[24] See **Appendix C. Class 8 FCET Costs** for this methodology.

Action Items

FCETs are currently more expensive than diesel trucks, and this incremental cost poses a serious barrier to market uptake. Although economies of scale will help to reduce the price of FCETs, there will still be a considerable incremental cost between FCETs and diesel trucks. The following actions can help to close this gap.

A. Fund the Deployment of 1,000 FCETs

CARB and CEC have provided funding for short-term HD FCET demonstrations and deployments, but more funding for demonstrations, especially longer-term projects, will help the Class 8 FCET market achieve scale and begin benefitting from higher production volumes—a necessary first step toward advancing the market from the current commercial vehicle scenario to the low-uptake scenario in Figure 9.

Fuel cells and onboard hydrogen storage tanks are responsible for a large portion of the price of an FCET and the incremental cost of the vehicle. The modelling provided in Figure 7 and Figure 8 indicates that a substantial decrease in the price of both components occurs after 1,000 FCETs are sold. As a result, CALSTART recommends providing funding for 1,000 FCET deployments to substantially increase production and kickstart economies of scale. This number of FCETs would result in significant price reductions for major components like fuel cells and onboard hydrogen storage tanks. In addition, this number of trucks would accelerate commercialization to Phase 3 (Growth). Of the current Class 8 truck fleet in California, 1,000 FCETs represents a small percentage. As of 2021, there were 219,000 Class 7–8 trucks in the state [CARB, 2022].

The State of California currently uses the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) to provide incentive funding for zero-emission vehicles. Under HVIP rules, vehicles can receive up to 50% of the incremental cost of the vehicle, or approximately $250,000 per FCET. Under these assumptions, about $250 million in funding would be required. Alternatively, the State of California could opt to accelerate the deployment of FCETs by covering the entire incremental costs of the vehicles, which would require $500 million. Between 2008 and 2022, the State of California awarded $1.287 billion in funding toward clean fuels and zero-emission vehicles/infrastructure initiatives via CEC's Clean Transportation Program [CEC, 2022]. The cost of this demonstration would therefore be less than the total amount that CEC's Clean Transportation Program has spent.

The primary objective of this action item is to reduce the cost of FCETs through economies of scale. However, based on the modelling in Figure 7 and Figure 8, fuel cells and onboard hydrogen storage tanks will not meet DOE price targets, even under the most optimistic

Class 8 FCET sales projections. Lowering the prices of these components is vital to decreasing the total cost of the vehicle: these two components are the most expensive zero-emission components on an FCET and comprise a significant portion of the price of the vehicle. (The price projections for fuel cells and onboard hydrogen storage tanks in Figure 7 and Figure 8 model only the economies of scale for the HD FCET market.)

It is highly likely that other vehicle types will convert to fuel cells. SCAQMD is currently funding a consortium to build an MD fuel cell paratransit bus [Ideanomics, 2022]. DOE also awarded funding to multiple OEMs to develop MD fuel cell electric Class 4–6 trucks through the SuperTruck 3 program, and CEC awarded funding to develop a fuel cell tugboat [DOE, 2021; CEC, 2021a]. As fuel cell technology is adopted in other transportation market segments, it is likely that economies of scale from those segments will spill over into the HD market and the FCET segment would benefit. As a result, increasing the adoption of fuel cell technology in other transportation market segments could help to narrow the gap between the projected price and DOE price targets.

B. Subsidize FCET Leasing Options

Because ZETs can be upwards of three times more expensive than conventional diesel trucks, higher upfront costs can be a roadblock to electric truck adoption. Upfront costs will decrease as these trucks scale in production volumes, but it is likely that upfront costs will remain higher than traditional Class 8 trucks. Alternative financing options are being explored to support ZET sales. Financing options act as a great method for ZET deployment, particularly for small fleets that cannot afford the capital investment of electric trucks and for large fleets not ready for a full investment in this technology. These financing options may become the standard for electric trucks for decades to come.

Numerous companies, both startups and established organizations, are looking to enter the electric truck leasing space. Many of these models will be a trucks-as-a-service model, which includes the upfront cost of the vehicle, charging costs, insurance, and maintenance costs all grouped into a leasing payment. There are several leasing payment models that can be adopted, including a cost per mile, a sliding cost scale based on miles driven each month, and a lease-to-own model. Some of these leasing models have started to emerge in the industry. For example, Watt EV, a startup seeking to help commercialize BETs, will provide fleet owners with several options for miles driven per month with an associated cost. Some financing organizations are purchasing electric trucks directly from OEMs like Volvo and Tesla. Others are working with third-party insurance brokers. These brokers purchase the trucks and lease them to fleet financers, who in turn lease the vehicles to fleets.

Fleet financers are predominantly partnering with OEMs to provide maintenance services for fleets. Because zero-emission technology is so new, specialized training from OEMs will be necessary to maintain the vehicles in the near-term until electric vehicle (EV) maintenance training becomes more available. Interviews with truck technicians at TEC Equipment, a Volvo dealership and Volvo's first certified electric truck maintenance facility, indicate that the industry will shift from in-house maintenance staff toward dealerships for electric truck maintenance. This model could work well for small fleets using leasing models for their electric trucks who currently do not have in-house maintenance staff.

Developing a leasing option for ZETs could allow smaller fleets and independent owner-operators to access trucks. Leasing models for BETs are being established, and many fleet financiers are expected to bundle all capital and operational costs into a trucks-as-a-service model. The market for leasing FCETs is much smaller due to the higher uncertainty surrounding the TCO of FCETs (see the previous **TCO Sensitivities** section). However, trucks-as-a-service is expected to be the dominant leasing model for FCETs. This model is especially useful for smaller fleets, which tend to be more risk adverse. Due to the disparity in capital costs between an FCET and a diesel truck, it is very likely that the leasing cost for an FCET will exceed that of a diesel or compressed natural gas (CNG) truck as FCET leasing models are developed. To allow smaller fleets to access FCET technology, it would be advisable for the State of California to develop a leasing subsidy for ZETs. This subsidy should be designed to offset the incremental leasing cost of an FCET so fleets can lease FCETs at a comparable cost as a diesel or CNG truck. Providing this option will increase the number of fleets who can adopt FCET technology.

To accelerate the development of FCET leasing models, more data will need to be gathered on the operational costs of FCETs. This research is required to provide clarity on TCO for FCETs. To facilitate this data collection, CALSTART recommends additional support for longer-term FCET demonstrations. (This action item is explained further under Promote Commercial Readiness and User Acceptance: **Action Item B. Fund Long-Term Pilot Projects**.)

Promote Commercial Readiness and User Acceptance

Commercializing FCETs will require educating fleets about hydrogen-powered vehicles, as well as further developing the technology so fleets can adopt FCETs with minimal changes to their operations. Addressing these issues can improve user acceptance of these vehicles, in turn helping accelerate commercialization. To promote commercial readiness and user acceptance, there are various technological and non-technological barriers to overcome. Education is the most prevalent non-technical barrier: many fleet owners do not understand the technology and need to be more informed before purchasing an FCET. Technologically, FCETs need increased durability and faster fuel times. Technology must meet current operational needs, so FCETs need the same performance level as fleets' current vehicles at a minimum. Ensuring that FCETs can meet this duty cycle is vital to promoting user acceptance.

Fleet Needs and Barriers

CALSTART interviewed a variety of fleets ranging in size and duty cycles to learn more about fleet operations and the operational performance needed from FCETs. Some small fleets had less than 25 trucks. Other fleets operate over 6,500 trucks across the state. The fleets operated duty cycles ranging from 100 to 500 miles per day. Almost all fleets interviewed deliver freight to and from the Ports of Los Angeles, Long Beach, Oakland, Stockton, or Hueneme. The fleets also varied in how many years they keep their trucks in service. One fleet operated their trucks for only two years before replacing them, while another aimed to keep trucks in service for 20 years. Finally, some fleets preferred to buy new trucks while others leased or bought used trucks.

Several fleet owners expressed that they did not know much about hydrogen technology but are interested in learning more. The majority felt that hydrogen trucking will be part of the solution to electrifying the freight sector and were interested in demonstrating the technology. Several large fleets interviewed have had demonstration projects with alternative fuels like natural gas, propane, or hydrogen. Negative experiences with pre-commercial technology left many wary of adopting new technology. In addition, they expressed concerns about who will perform maintenance. However, many fleet owners interviewed were either interested in or plan to adopt fuel cell technology because of its operational benefits relative to BETs:

- 300- to 500-mile range
- Quick refueling (15–20 minutes)
- Public fueling
    - With public fueling, fleets do not need to install infrastructure onsite, saving them time and reducing capital expenditures (CAPEX). In addition, FCET fleets will not be as reliant on the grid, which would cause problems in the event of a grid outage [Lozano, 2021].

These benefits are especially appealing to fleets operating routes longer than 300 miles. The Volvo Low Impact Green Heavy Transport Solutions (LIGHTS) project found that Class 8 Volvo VNR electric trucks could operate up to 150 miles per day with two to three opportunity charges, or about 90 miles on a single charge [Volvo Group North America, 2022]. FCETs are also well-suited to independent owner-operator needs. CALSTART's interviews of drayage fleets found that independent owner-operators are generally placed on more demanding duty cycles because they are often paid per trip rather than per hour, which incentivizes them to drive quickly and minimize breaks. Many independent owner-operators will not want to wait hours for an electric truck to charge and will not be able to install onsite charging infrastructure. FCETs fueled by public stations therefore present an excellent solution for independent owner-operators' needs.

Technology Readiness

As discussed previously, despite an increased TRL score of seven as of this writing, FCETs will still need to undergo further technological development to increase commercial readiness. In order to be commercially viable, fleets need FCETs to meet their service needs without having to change their operations. DOE recognizes that FCET technology needs to continue improving to meet the needs of fleets. As mentioned in the **Vehicle Costs and Component Cost Contributions** section, DOE released performance targets for Class 8 FCETs. These targets (Table 4) set an interim goal for 2030 and an ultimate goal for 2050. In addition to reductions in fuel cell system and hydrogen storage system costs, DOE calls for an increase in fuel cell system lifetime/durability, an increase in the fuel cell peak efficiency, and an increase in the hydrogen fill rate. It also sets a goal for the storage system life cycle and the pressurized storage system life cycle. The most important DOE technical target is durability, set at a 30,000-hour PEMFC lifetime, equivalent to 1 million miles driven.

Table 4. Technical System Targets: Class 8 Long-Haul Tractor Trailers [DOE, 2019]

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate
Fuel Cell System Lifetime[1,2]	Hours	25,000	30,000
Fuel Cell System Cost[1,3,4]	$/kW	80	60
Fuel Cell Efficiency (peak)	%	68	72
Hydrogen Fill Rate	Kg of hydrogen /min	8	10
Storage System Cycle Life[5]	Cycles	5,000	5,000
Pressurized Storage System Cycle Life[6]	Cycles	11,000	11,000

Characteristic	Units	Targets for Class 8 Tractor-Trailers	
		Interim (2030)	Ultimate
Hydrogen Storage System Cost[4,7,8]	$/kWh ($/kg of hydrogen stored)	9 (300)	8 (266)

1. *The fuel cell system excludes hydrogen storage, power electronics, batteries, and electric drive.*
2. *The lifetime target is intended to cover the entire useful life of the vehicle. Fuel cell system lifetime is defined as hours of use with an appropriate duty cycle that considers real world driving conditions (i.e., not steady state operation). Corresponding vehicle lifetime range is 1M miles (Interim) and 1.2M miles (Ultimate) based on an average speed of 40 mph.*
3. *Interim and ultimate cost targets assume 100,000 units per year production volumes (except where specified within parenthetical references). Note that meeting fuel cell and hydrogen storage component cost targets may require leveraging automotive production volumes to achieve the necessary economies of scale for cost competitiveness. Current (2019) heavy-duty vehicle fuel cell technology was estimated to cost ~$190/kW at 1,000 units per year manufacturing volume (Fuel Cell Systems Analysis, 2019 DOE Hydrogen and Fuel Cells Program Review Presentation, https://www.hydrogen.energy.gov/pdfs/review19/fc163_james_2019_o.pdf).*
4. *Costs are in 2016 dollars.*
5. *The storage system cycle life target is intended to represent the minimum number operational cycles required for the entire useful life of a vehicle used in long-haul operation. This target is technology agnostic.*
6. *Pressurized storage systems must meet cycle life requirements in applicable codes and standards (i.e., SAE J2579 and United Nations Global Technical Regulation No. 13). These codes and standards cycle life requirements require significantly more cycles than Storage System Cycle Life. For example, the baseline initial pressure cycle life in the United Nations Global Technical Regulation can require 11,000 cycles for a heavy-duty application.*
7. *Hydrogen storage system cost includes the storage tank and all necessary balance-of-plant components. This target is technology agnostic.*
8. *Current (2019) 700 bar hydrogen storage system was estimated to cost ~$36/kWh at 1,000 units per year manufacturing volume and $15/kWh at high volume (extrapolated from DOE Hydrogen and Fuel Cells Program Record #15013 "Onboard Type IV Compressed Hydrogen Storage System—Cost and Performance Status 2015," https://www.hydrogen.energy.gov/pdfs/15013_onboard_storage_performance_cost.pdf). Note: Hydrogen storage targets will be updated and are currently based on U.S. DRIVE fuel cell electric vehicle targets.*
9. *Analysis based on 2050 simple cost of ownership assumptions and reflects anticipated timeframe for market penetration.*

Current Efforts to Advance Commercialization

The majority of DOE's technical targets address component/system cost, component/vehicle durability, or hydrogen fueling speed. Improvements will need to be made in each of these three categories to make FCETs more attractive to fleets and to help commercialize the technology. Efforts to reduce component/system costs through economies of scale were outlined previously in **Reduce Upfront Costs and TCO**; this section will focus on efforts being taken to improve durability and hydrogen fueling speed.

Million Mile Fuel Cell Truck Consortium

Durability refers to how long an FCET or its components/systems can operate without needing to be replaced. Replacing components/systems is expensive, so lack of durability harms the business case for adopting FCETs. In addition, improved durability increases the lifetime of the truck.

In Class 8 diesel trucks, the engine is often the main system that experiences durability issues. Class 8 trucks have a rigorous duty cycle, and the engine suffers from wear and tear, typically requiring a midlife rebuild. The equivalent system in an FCET is the fuel cell. To compete with a diesel truck, the fuel cell engine will need to have durability equivalent to a diesel-powered internal combustion engine.

DOE has provided support to help fuel cells become more durable and to meet its performance targets. In 2020, DOE launched the Million Mile Fuel Cell Truck Consortium (M2FCT) consortium, which includes Los Alamos National Laboratory, Lawrence Berkeley National Laboratory, Argonne National Laboratory, National Renewable Energy Laboratory (NREL), and Oak Ridge National Laboratory. The objective of M2FCT is to improve the efficiency and durability of PEMFCs to help facilitate their commercialization. M2FCT aims to extend the lifetime of PEMFCs to 25,000 hours of operation by 2030, with an ultimate goal of achieving a lifetime of 30,000 hours by 2050. This goal equates to a fuel cell lifetime of 1 million miles, which is the approximate life of a diesel truck.

M2FCT has worked toward its objectives by funding academic research. It has also started several working groups that work toward addressing key research areas. To date, M2FCT has launched the Accelerated Stress Testing Working Group, which is developing accelerated stress tests that can be used to assess whether fuel cells can meet the performance targets without having to test the fuel cell over a complete life cycle. M2FCT has also convened the International Durability Working Group, which has representation from the United States, the European Union, Japan, and Korea. This working group is conducting research on stressors that reduce the durability of PEMFCs, the characteristics of PEMFC materials that suffer from degradation, and the structural changes that occur in components throughout the life of the PEMFC.

High Flow Hydrogen Fueling Standards and Protocols

One of the advantages that an FCET has over a BET is that it can refuel as quickly as conventional vehicles. A BET can take hours to recharge, but an FCET can refuel in a matter of minutes. While an FCET can refuel quickly, it still fuels at a slower rate than a diesel vehicle. Fleets need to maximize the utilization of their vehicles and would prefer to reduce labor costs associated with refueling. As a result, most fleets would prefer that FCETs fuel at least as fast as a diesel vehicle.

Fueling speed for MHD commercial fuel cell electric vehicles (FCEVs) is limited by existing fueling infrastructure and components (e.g., nozzles). During refueling, the expansion of hydrogen into the hydrogen tank generates heat. Onboard hydrogen storage tanks can be heated only to the certified temperature of the storage system before risking degradation and compromising the integrity of the tank. Fueling standards and protocols were established to ensure that the tank temperature remains within safe ranges throughout the fueling process.

- SAE J2601 currently provides fueling standards for light-duty FCEVs at a pressure of 350 bar (H35) and 700 bar (H70). It also allows fueling for tanks that have a maximum storage capacity of 10 kg.
- SAE J2601/2 provides a protocol for fueling HD buses at H35. This is a technical guidance document rather than a full standard.
- SAE J2601 is not sufficient for MHD vehicles. SAE J2601 allows for fueling at a maximum rate of 60 grams per second (g/s) (3.6 kg per minute). This rate, however, is far below an average rate of 10 kg per minute, which is the diesel-equivalent fueling rate for a Class 8 truck. In addition, while some trucks in Europe will fuel at H35, most OEMs are planning to fuel trucks at H70. HD trucks are also expected to have a larger tank system (40–100 kg).
- SAE J2601-3 provides a protocol for fueling forklifts at H70. This is a technical guidance document rather than a full standard. A protocol for high-flow, HD fueling at H70 needs to be developed.

During a small-scale demonstration, the fueling rate will not make a significant difference as the trucks can be fueled overnight. As FCETs are deployed at scale, the time required to fuel the entire fleet will increase, meaning a faster fueling rate will be required to support larger truck deployments.

Fueling standards and protocols are being developed to increase the speed of hydrogen fueling. Work is being done to adapt J2601 for faster fueling at H35. This standard is called H35 High Flow (H35HF) and is intended to be used to fuel MHD vehicles. This work is being funded by DOE's H2@Scale Program in partnership with NREL, SoCal Gas, Shell, and Frontier Energy. SCAQMD has also provided funding for this project. In this project, NREL will model tank conditions during fueling and will confirm results by dispensing hydrogen with a high flow nozzle into an HD vehicle simulator. A hydrogen fueler with a high flow nozzle and H35HF fueling protocols will also be deployed for testing under real-world conditions at SunLine Transit. This project will help to accelerate the development of H35HF fueling standards and protocols, which will help to advance the commercialization of FCEVs [SCAQMD, 2021].

California has put forth effort to help support the development of an H35HF standard. However, many OEMs are planning to produce trucks that will fuel at H70. Current light-duty hydrogen fueling standards allow for a dispensing rate of 60 g/s (3.6 kg of hydrogen per minute) at H70. The rate that diesel can be pumped into a truck is equivalent to about 10 kg per minute. High-flow HD hydrogen fueling infrastructure must be developed to close this gap in fueling time between hydrogen and diesel.

Initiatives are currently focused on this issue. Protocol for Heavy-Duty Hydrogen Refueling (PRHYDE) in the European Union aims to develop concepts that will be used to develop standards for H70 fueling at peak rates above 60 g/s. SAE is adopting some of PRHYDE's approach to develop 120 g/s as an interim fueling option (J2601-5). ISO TC 197/WG24 is working in parallel to develop an H70 standard for fueling at a rate of up to 300 g/s. PRHYDE and ISO TC 197/WG24 are investigating the behavior of gaseous hydrogen inside the tank as it fills at peak rates of up to 300 g/s. So far, most of the work done by these initiatives has been to develop models that simulate hydrogen behavior to ensure that it remains within safe temperature parameters (85 degrees Celsius or below). DOE also supports efforts to increase fueling rates. As shown in Table 4, DOE has a goal of an average fill rate of 8 kg per minute (133.33 g/s) by 2030 and an ultimate goal of 10 kg per minute (166.67 g/s). These targets were designed to allow an 80 kg storage system to refuel in 10 minutes.

These models were validated with real-world data. NREL launched the Innovating High Throughput Hydrogen Stations Project to support this validation project. Under this project, NREL designed and built a fast-flow HD hydrogen fueling test station. This test station dispenses hydrogen to a bank of hydrogen storage tanks to simulate fueling to a vehicle. This project demonstrated a hydrogen fast fill. During this demonstration, the station achieved an average fill rate of 14 kg per minute and filled 40.3 kg into the hydrogen storage tanks in 2.87 minutes. The ultimate goal is to fill 60–80 kg of hydrogen in under 10 minutes [Martineau, 2022]. The test results from NREL's demonstration will be shared with the public to help support hydrogen station stakeholders. NREL already has the H2FillS program which models the behavior of hydrogen during fueling. This model will be updated for HD hydrogen fueling based on the results of this demonstration [Peters, 2021].

Action Items

Both federal and state governments have put forth several initiatives to help advance commercial readiness for FCETs. However, these efforts will need to go beyond developing the technology. Customers must be comfortable with the technology before they are willing to purchase these vehicles. CALSTART has identified several actions that can be taken to increase fleet owners' knowledge of FCETs.

A. Develop FCET Loaner Programs

Many of the fleet owners CALSTART interviewed stated that they were not familiar with fuel cell technology or hydrogen fuel; this is highly problematic given familiarity is a major factor in a customer's decision to adopt a new technology. As seen in Table 5, the Innovation-Decision Model describes how customers adopt new technologies—a decision-making process that goes through several stages.

Table 5. Innovation-Decision Model [Rogers, 2003]

Stage	Characteristics
Knowledge	The customer learns about a new technology and how it works.
Persuasion	The customer develops an opinion, either positive or negative, toward the new technology.
Decision	The customer decides to adopt or not to adopt the new technology.
Implementation	The customer adopts and uses the new technology.
Confirmation	The customer seeks information to confirm or reverse their decision to adopt the new technology.

Familiarity with FCETs is a prerequisite for adoption. Helping fleets understand FCET technology will help bridge this current knowledge gap and encourage more fleets to consider adopting Class 8 FCETs. It is important to note that previous experience with alternative fuels can also affect willingness to adopt FCETs. Access to education could help to assuage the concerns fleets may have due to a previous negative experience with alternative fuels.

FCET OEMs will need to aggressively market FCETs to increase awareness about the technology. One approach is to establish a loaner program for FCETs. This program would allow fleets to borrow a truck for a period of time and use it in real-world service, helping fleets gain operational experience with fuel cell technology.

California is working on a loaner program for alternative fuel vehicles. Assembly Bill (AB) 617, signed in July 2017, requires new community-focused action to reduce air pollution and improve public health in areas disproportionately burdened by air pollution. CARB designated several communities as AB 617 Communities; steering committees were set up in each area to develop a Community Emission Reduction Plan (CERP). One of these AB 617 Communities is Wilmington, Carson, West Long Beach (WCWLB). A main priority for WCWLB CERP is reducing air pollution from HD trucks. CERP proposes developing an incentive program to accelerate the adoption of cleaner HD trucks, with an emphasis on ZETs [SCAQMD, 2019]. CARB found that existing incentive programs were not appropriate for small fleets and businesses as they cannot afford ZETs. CARB held community workshops to solicit feedback on designing an effective incentive program for these constituents [SCAQMD, 2021a]. Workshop participants indicated support for an electric truck loaner program: short-term trials with BETs would allow fleets to gain operational experience and knowledge of BETs and minimize financial risks. Certain challenges to implementing this program would include providing charging options, selecting participants, matching fleets with appropriate vehicle types, and developing loan terms (duration, insurance requirements, training, etc.).

FCETs will not be included in this program initially given that these vehicles are still considered prototypes [SCAQMD, 2022]. However, including FCETs in this program would help to accelerate knowledge of fuel cell technology, increasing fleet owners' comfort in operating and willingness to adopt these vehicles. For a loaner program to be successful, fleets also need access to a hydrogen fueling solution, which can potentially be fulfilled by loaning a mobile hydrogen fueler to fleets participating in the program. As user understanding and acceptance grows, so will demand.

B. Fund Long-Term Pilot Projects

Most FCET demonstration projects that have been funded to date last for only a year or two. This has occurred because advanced vehicles are pre-commercial technologies and are typically operating under an experimental permit. The experimental permit lasts for one year but can be renewed for an additional year, for a total of two years. While these demonstrations are valuable and have shown that demonstration vehicles can operate without major problems or breakdowns, this length of time does not provide a full picture of the maintenance and repair needs of the vehicles.

Vehicles need to be in operation for about five years to get an accurate estimate of maintenance and repair needs. CALSTART's interviews indicate that most Class 8 vehicle leases last approximately five years and that many fleets try to replace their fleet after about five years. Over this period, trucks will have more serious breakdowns and will need more extensive repairs. The data gathered will allow OEMs to learn more about the durability of their trucks and which systems are most likely to need repairs over the length of a typical lease/length of ownership of a truck.

This data can be obtained by launching a five-year pilot project for FCETs. While pre-commercial vehicles can only operate for up to two years under an experimental permit, commercial vehicles can be permitted under an executive order from the Governor for longer. As a result, CALSTART recommends that industry pursues a pilot project once an OEM develops a vehicle that can be permitted under an executive order.

The real-world data gathered from a long-term pilot project could complement the work done under M2FCT and generate data that can be used to further the research conducted under this program. This pilot would also help establish certainty on maintenance and repair costs over the lifetime of the vehicle. Fleets cannot accurately complete financial/business planning with a high level of uncertainty about the costs of operating FCETs. In addition, information gathered from long-term demonstrations will help establish residual values, the value of the trucks in secondary markets, and the development of leasing models. The experience from a pilot could also assist OEMs in developing the next generation of their vehicles, parts, repair supply chain, and technician workforce, as well as scaling up their production lines.

C. Develop Intermediate Fast-Flow HD Fueling Standard

PRHYDE and ISO TC197/WG24 are working on developing options for HD high flow fueling. However, developing and finalizing these options is a lengthy process that can take years. There are steps to increase the speed of fueling before PRHYDE and ISO TC197/WG24 complete their work. ISO 17268 and SAE J2600 have outlined a new hydrogen fueling receptacle geometry that can facilitate flow rates of up to 90 g/s (5.4 kg per minute), which represents a 50% increase in fueling. Although this design has been outlined in ISO 17268/SAE J2600, there are no fueling standards to date to support flow rates of up to 5.4 kg per minute.

To develop a standard, SAE J2601 can be modified. SAE J2601-5 was introduced as a technical guidance document to achieve flow rates of up to 120 g/s. This technical guidance document is currently going through the SAE adoption process. However, this document is prescriptive rather than standard. To develop a binding standard, SAE J2601 Category D can be updated to support fueling at 120 g/s for H35 and 90 g/s for H70. Many of the fueling parameters that are established in Category D have coefficients that are based on the flow rate (mass per second). Currently these coefficients assume a flow rate of 60 g/s. Updating these coefficients based on 120 g/s for H35 fueling and 90 g/s for H70 fueling would effectively establish an SAE standard for these fueling options. This update can occur while ISO continues development on 300 g/s protocol.

As standards are updated, nomenclature for fueling rates will also need to be revised. Historically, fueling has been denoted by tank pressure. H35 has denoted 350 bar fueling, and H70 has denoted 700 bar fueling. Since there have been attempts to deploy high flow standards, "HF" has been added to the end to denote high flow standards. For example, H70HF would denote high flow H70 fueling. However, there are multiple flow rates that are being considered as "high flow." As a result, the HF designation is not sufficient to differentiate between these rates. One way to update the nomenclature is to denote fueling speed in g/s. Instead of using the HF designation, fueling would be designed as H70FX, where X is equal to the flow rate in g/s. For example, under this designation, H70F300 would designate H70 fueling at a flow rate of 300 g/s.

The existence of standards for fueling at different flow rates will introduce an interoperability issue. Industry will need to remain vigilant to ensure that interoperability issues do not create a safety issue. To take advantage of these faster fueling standards, both the vehicle and the station will need to have proper hardware (i.e., nozzles and receptacles). Stations will need to be designed so that fueling cannot take place without the proper hardware. For example, if the fueling station has a nozzle that can support high flow fueling but the truck's receptacle does not, then the station needs to be redesigned so fueling at this rate is not possible. To facilitate this, nozzles that support fueling at different flow rates should not be mechanically compatible (i.e., a fueling station's H70F90 nozzle should not fit into a truck's H70F60 receptacle).

Communications protocols between the vehicle and the station must also be developed. The vehicle and the station will need to communicate to ensure that both have the correct equipment to safely fuel at a particular fueling rate. Industry needs to come to a consensus on a communications protocol to ensure that fueling can occur only when safe to do so.

Address Other Enabling Factors

Many of the barriers to FCET commercialization are either economic or technological. However, other factors, known as enabling factors, can pose barriers to the development and maturity of this market. These enabling factors, if addressed, will make it easier for fleets to deploy FCETs; if no action is taken, these factors will create severe inconveniences for fleets that can also have financial implications and discourage FCET uptake.

Weight Penalty

ZETs weigh more than diesel trucks due to heavy components like traction motors, regenerative braking systems, and batteries, especially those in BETs [NACFE, 2021]. Although the primary powerplant is the fuel cell, FCETs also have a small battery. Taken together, these factors mean that both BETs and FCETs weigh more than a diesel truck.

All internal combustion engine-powered Class 8 trucks are subject to a federal weight limit of 80,000 pounds gross weight. These limits are intended to ensure driver safety (i.e., so the vehicle can stop quickly), limit road degradation, and ensure bridges can support truck weight. ZETs weigh more than diesel trucks, but since they are still subject to a weight limit, they suffer a penalty. Diesel trucks weigh about 17,000 pounds whereas Class 8 FCETs weigh about 22,000 pounds [Office of Energy Efficiency & Renewable Energy, 2010; Adler, 2021]. ZETs must offset this weight by reducing their cargo weight, which cuts into profits for fleets. There have been attempts to mitigate this problem:

- The Fixing America's Surface Transportation (FAST) Act allows federal programs to provide guidance on truck size and weight provisions. The FAST Act allowed federal programs to provide this guidance for natural gas trucks and increase the weight limit for natural gas trucks to 82,000 pounds [Caltrans, n.d.].[25]
- California AB 2061 (2017-2018) which extends the FAST Act guidance to "near-zero emission vehicles" and "zero-emission vehicles."[26]

These policies create a 2,000-pounds exemption for ZETs and increase the weight limit for ZETs to 82,000 pounds. However, the extra 2,000 pounds from the weight exemption does not offset the increased weight of an FCET. The resulting 3,000-pounds weight penalty (i.e.,

[25] For more information about the FAST Act, visit https://www.congress.gov/bill/114th-congress/house-bill/22/text.

[26] For more information about California AB 2061 (2017-2018), visit https://leginfo.legislature.ca.gov/faces/billVotesClient.xhtml?bill_id=201720180AB2061.

diesel to FCET weight difference minus the exemption) will have an impact on fleets' finances, as it will reduce the amount of cargo each truck can carry.

CARB recently released its Large Entity Fleet Reporting Report. In 2020, CARB adopted a regulation that required large entities that operate vehicles with a gross vehicle weight rating (GVWR) of greater than 8,500 pounds in California to report information about their fleets for this study. It states that 54% of truck day cabs and 58% of truck sleeper cabs typically operate at their weight limit [CARB, 2022b]. These results indicate that the weight penalty for ZETs will be an issue for many operators.

Lack of Specialized Workforce

Electrified drivetrains are a fundamentally different technology than internal combustion engines. The current workforce has extremely limited experience with electrified drivetrains and does not have the skills required to repair and maintain this technology. Therefore, the availability of vehicle technicians who can repair and maintain this technology will place limits on vehicle deployments. This problem is even more pervasive for FCEVs as workers must have additional knowledge of hydrogen and fuel cells, in addition to knowledge of electrified drivetrains, to effectively work with this technology.

Two types of workers are needed to support the deployments of FCETs:

- Vehicle technicians perform maintenance and repairs on vehicles. Technicians need to be proficient in high voltage electrical circuits and safety, batteries and battery management systems, and high-pressure gas and hydrogen safety. In addition, vehicle technicians must be proficient in traditional vehicle mechanical systems like suspension; steering; brakes; and heating, ventilation, and air conditioning. Technicians tend to have specialized skillsets on certain vehicle systems. Most vehicle technicians receive their training from a community college or trade school before receiving on-the-job training once hired by a fleet.
- Engineers have in-depth knowledge on how all systems on the vehicle interact with each other and how the entire vehicle is constructed. Engineers can also develop expertise in hydrogen fueling and production infrastructure. Engineers work on tasks like troubleshooting for advanced problems on the vehicles, product design, and research and development. Engineers require a bachelor's or master's degree from a four-year university.

The zero-emission industry is currently lacking both engineers and technicians. While the transit agency has technicians, they are already experiencing backlogs in upskilling their workforce so they can maintain and repair zero-emission buses [Bus & Motorcoach News, 2022; Veeder, 2019]. This problem will become more pronounced as sales of other zero-emission vehicles, like FCETs, increase. Truck fleets will likely experience a similar challenge as they begin to purchase and deploy FCETs.

Manufacturing

To meet the minimum requirements of the ACF rule, large numbers of FCETs will need to be deployed quickly. Manufacturing is a major constraint on FCET deployments. FCETs can be deployed only if manufacturing can keep up with market demand and if they can be manufactured in a timely manner. Since FCETs are a newer technology and are currently being manufactured in low quantities, industry's ability to meet market demand is a legitimate concern. Other zero-emission vehicle sectors appear to be having problems with increasing manufacturing. The zero-emission transit bus sector has experienced growing backlogs due to supply chain disruptions caused by the COVID-19 pandemic and the Ukraine-Russia war [Zukowski, 2022]. The FCET industry will likely face similar challenges.

Since FCETs are in an earlier stage of development, OEMs do not currently have an established manufacturing process that can mass produce these vehicles. OEMs will need to take action to increase their manufacturing capacity. However, since production volumes are currently low, making investments in FCET manufacturing ahead of market demand is risky from a business standpoint and can impose costs on OEMs—the market may take longer than expected to reach the estimated demand or might fail to meet the projected demand at all. If this scenario were to occur, OEMs would have either idle assets or stranded assets, a costly problem. In addition, OEMs need to be sure that increasing manufacturing for FCETs does not disrupt manufacturing for other vehicle segments. OEMs will need to navigate this challenge to scale production to meet market demand.

Action Items

To address these enabling factors hindering FCET adoption, CALSTART recommends that the following actions are taken.

A. Incentivize Lightweighting Technology

With Class 8 FCETs facing a weight penalty of about 3,000 pounds, several fleets interviewed for this project requested a greater exemption to mitigate this penalty, but prospects for the establishment of a greater weight exemption are not promising. There are two barriers to increasing the weight exemption. First, the California Highway Patrol (CHP) operates under the idea that as batteries improved and energy density increased over time, ZETs would become lighter. CHP assumed that the increased road degradation from the increased truck weight would be temporary. Convincing CHP to increase the weight limit further is therefore unlikely. In addition, OEMs would have to reconfigure their vehicles to allow for increases in the weight limit. There are limits on how much weight can be on each axle. If the weight of the truck increases, they would likely need an additional axle or a tandem axle to meet this requirement. OEMs are unlikely to be willing to change the design of their vehicle due to associated costs.[27]

The most promising approach to address the weight penalty is the adoption of vehicle lightweighting practices. Lightweighting involves modifying the design of or using lighter materials on the truck or trailer to reduce its overall weight. The North American Council on Freight Efficiency (NACFE) released its Lightweighting Confidence Reports, which document research on techniques for lightweighting Class 8 trucks. Some of these techniques involve changes in materials, and others involve reducing the size of the equipment on the truck (i.e., using a lighter engine). This report focuses primarily on diesel trucks, so some of these techniques will not be relevant to FCETs. Furthermore, some techniques outlined in the report involve reducing the size of the equipment, which decreases the abilities of the truck. These techniques were deemed unacceptable for FCETs.

Some of the NACFE report's techniques include replacing steel components (such as the driveshaft or wheelbase) on FCETs with aluminum components, replacing steel with aluminum in the cab, and using paint film instead of liquid paint. These alternatives would lead to an 800-pounds weight reduction. Trucks can be lightweighted by replacing the wood flooring with a lighter weight laminate/resin fiber composite material, using aluminum wheels instead of steel wheels, and replacing steel structural components with aluminum. This approach would lead to a 2,262-pounds weight reduction.

CALSTART recommends that these lightweighting techniques be incorporated by OEMs and that a commercial lightweight truck and trailer should be made available. Lightweighting can improve fuel savings, freight efficiency, driver retention (i.e., making it possible to specify driver amenities that add weight), regulatory compliance, and sustainability. These benefits would improve fuel economy and increase the cargo load capacity for traditional Class 8 trucks and would allow ZETs to offset some of the weight penalty. The key barriers to this solution, however, include upfront costs that may not have an attractive payback, possibly lower resale values, and shorter durability compared to heavier counterparts.

[27] Interview with Bill Van Amberg, former vice president of CALSTART, who was involved in advocating for the original 2,000 pounds weight limit exemption.

More investment in lightweighting is needed to fully realize its benefits. OEMs like Tesla and Nikola are working to optimize their electric trucks, which includes lightweighting. Bus manufacturers have begun to experiment with using carbon fiber composite to construct the body of the bus, which could reduce the weight of the bus by 8,000 pounds. Carbon fiber composite may also be used to build the trailer body, potentially reducing the weight of the trailer by 4,000 pounds. These early steps by OEMs will still benefit all fleets as the practice scales and becomes cheaper [Wickenhauser, 2021]. Further research into lightweight materials should be pursued as well to decrease the cost of lightweight materials and increase their durability.

B. Fund Workforce Development Initiatives

The transition to FCETs can create new jobs and provide economic opportunities and benefits to the State of California. To capture these benefits, a workforce must be formed that can support the deployment of FCETs. The zero-emission vehicle industry is already experiencing a shortage of technicians and engineers. The assurance of an adequate workforce is required to encourage the development of a hydrogen economy in California and continued industry investment in the state. The number of technicians and engineers must increase to serve the growing number of FCET deployments.

Currently, only a few community colleges exist that offer technicians training in zero-emission vehicles. Rio Hondo College in Whittier, California, has a unique zero-emission vehicles program that provides training specific to HD zero-emission vehicles, including FCEVs. San Bernardino Valley College also has an automotive program that focuses on MHD trucks. However, this program does not yet provide instruction for fuel cell technology. The California Community College system will expand programs for FCEVs when there is proven demand. However, the Advanced Clean Trucks (ACT) regulation will mandate that ZET sales begin in 2024 and more fuel cell automotive programs will need to be established to support these vehicles [CARB, 2021a]. These trucks are expected to be deployed primarily in the Los Angeles-Inland Empire, San Diego, Bay Area, and Central Valley regions. Since there is already a program in the Los Angeles-Inland Empire area, one community college in each of the San Diego, Bay Area, and Central Valley regions should develop a fuel cell automotive program to begin training workers.

As of 2018, there were approximately 24,600 bus and truck mechanics employed in California. The number of bus and truck mechanic jobs is projected to increase to 26,500 by 2028. Of these mechanics, 14.1% work for truck companies and 12.3% work for merchant wholesalers who operate trucks. Over a quarter of these mechanics will therefore work directly on trucks [Employment Development Department, 2022]. However, other HD vehicles, like transit buses, are also transitioning to zero emissions. Since the skills required to maintain a zero-emission bus are similar to maintaining a ZET, there will be fierce competition for mechanics who can maintain and repair zero-emission technology. The majority of present-day workers will need training to learn how to operate on ZETs; most existing bus and truck mechanics will need to be upskilled to work on these new technologies. In addition, there will be opportunities to train new workers as the current workforce retires and the trucking industry grows.

The California Community Colleges system will expand programs once demand/enrollment is proven. Establishing a new accredited program can be a lengthy process, but industry can help to accelerate it. Community colleges offer contract education programs with not-for-credit courses taught by community college staff. While these programs do not offer college credit, they do provide workers with training. Industry must fund contract education programs and typically assist in curriculum development. OEMs and fleets can fund contract education programs at community colleges to establish a training program so existing workers can update their skillset and be able to work on zero-emission vehicle technology. These programs can also be used to train new technicians entering the workforce. The establishment of contract education programs can accelerate the deployment of zero-emission automotive programs at community colleges by piloting curriculum and helping demonstrate demand for the program.

Universities and four-year colleges are vital to training vehicle engineers. A good model for increasing the number of engineers would be to develop research centers that facilitate partnerships between universities and industry. The university would host a research center that has a specialty on hydrogen-related technology (e.g., fuel cells, hydrogen fueling infrastructure, etc.). Industry would then provide training to faculty at each research center and collaborate to develop curriculum. Funding needs to be secured for these facilities, which usually cost around $2 to $3 million.[28]

Research centers can offer capstone projects in which an industry partner comes to the university with a specific project for students. These projects feature an engineering challenge for fuel cells that needs to be solved. The industry partner funds the capstone project (usually $10,000–$40,000 per project) and provides a mentor. Teams of students are recruited to work on the project and solve the engineering challenge. Through this process, students learn project management skills and technical skills. Students who participate are job-ready and highly employable at the end of the project. Industry can also fund internships to provide students with experience working on fuel cells and hydrogen stations.

[28] Information provided by Professor David Blekhman of California State University, Los Angeles.

Investing in research centers will develop human capital and a strong engineering workforce in California, encouraging further industry investment in the state's hydrogen economy.

C. Scale Up FCET Manufacturing Capacity

OEMs will need to increase their manufacturing capacity to meet market demand, but managing the transition from manufacturing internal combustion engine Class 8 trucks to FCETs will be challenging. OEMs will need to ensure that their investments in FCET manufacturing do not disrupt their current operations and do not become stranded assets in the future. The transit bus sector has already begun this transition, and the school bus sector is preparing to make this transition. The manufacturing practices that these sectors adopted can provide guidance for the FCET sector. There are multiple legacy OEMs in the transit bus and school bus sectors who historically manufactured internal combustion engine vehicles before transitioning to manufacturing zero-emission buses. Major truck OEMs are in an analogous situation, and they would be the truck sector's equivalent of legacy OEMs.

Legacy OEMs already have an established manufacturing process for internal combustion engine vehicles and are already engaged in serial production. These OEMs employ an assembly line process, which consists of multiple workstations in series. Each workstation is assigned a certain task in the manufacturing process. Certain components and systems are added to the vehicle at each workstation. Once the component or system has been added, the vehicle is moved to the next workstation for a different component or system. Once the vehicle has been moved from the first workstation, the first workstation is now available for another vehicle.

OEMs can adopt an alternative manufacturing process to scale up manufacturing capacity: a parallel assembly line, which is a variation of a normal assembly line. The main premise behind this alternative process is that there are many similarities in manufacturing internal combustion engine trucks and FCETs. These vehicles have multiple components in common, such as the chassis and the cab. The main differences between the two vehicle types are the drivetrain and the zero-emission components. As a result, the two vehicle types can use the same assembly line until the drivetrain and the zero-emission components need to be installed. At that point, the truck is removed from the main assembly line and sent to a parallel assembly line for the drivetrain and zero-emission components.

This production method is beneficial because it allows a legacy OEM to produce FCETs with minimal changes to the manufacturing facility and without disrupting the production of other vehicle types. This production method is also scalable. As FCETs comprise an increasing share of sales, additional assembly lines can be converted to parallel assembly lines. As FCETs become the dominant share of sales, the parallel assembly line layout can revert back to a traditional assembly line, but one that produces FCETs. This production method also minimizes risk by reducing the potential for stranded assets.

It is important to note that some stakeholders in the FCET market are not vertically integrated. Instead, some stakeholders aim to produce FCETs by integrating a fuel cell into an OEM's Class 8 truck. Integrating a fuel cell will require a deep level of collaboration between the OEM and the fuel cell manufacturer. This collaboration will require a significant amount of engineering work to optimize the fuel cell for operation onboard the OEM's truck. Any engineering or design changes that were made to integrate the fuel cell will need to be replicated in the manufacturing process.

Based on correspondence with FCET stakeholders, there is industry interest in building FCETs through the integration approach. Fuel cell manufacturers have been analyzing the FCET market and have made commitments to work with OEMs to integrate fuel cells and demonstrate FCETs. FCET manufacturing through the integration approach is expected to scale up to meet customer demand within the next three to five years.

III. Hydrogen Infrastructure Roadmap

Hydrogen infrastructure is a key aspect of FCET commercialization. When fleets purchase HD FCETs, they will need access to this infrastructure to operate these vehicles. California is a national leader in both the battery-electric and FCEV sector, but the state's hydrogen market is still in the early stages of development. Light-duty FCEVs are already a commercial technology, but only 56 public light-duty hydrogen fueling stations have been constructed as of October 2022 [Hydrogen Fuel Cell Partnership, 2022]. The hydrogen market for MHD vehicles is also nascent, especially given that MHD FCEVs are in earlier stages of development than light-duty vehicles. Furthermore, there are few vehicle applications for which a fuel cell option exists. California is an early mover in the MHD FCEV market, being one of the first adopters of fuel cell electric buses (FCEBs). However, despite being an early adopter, only 211 FCEBs have been funded, ordered, and/or delivered in California as of 2022 [Chard et al., 2023].

While transit agencies are learning from early FCEB deployments, many of these learnings are not fully transferable to the FCET sector. FCEBs have predictable routes and return to their depot every night. As a result, they typically use private hydrogen fueling stations and rarely, if ever, use public hydrogen fueling stations. FCETs have a different duty cycle: many have unpredictable routes and conduct long-haul service, which precludes returning to their depot on a nightly basis. These FCETs will be heavily reliant on a public hydrogen fueling network and will need access to stations that are capable of fueling HD vehicles. This hydrogen fueling network is currently underdeveloped; at the time of writing, only four public hydrogen stations can serve MHD vehicles in California. Furthermore, since the FCEV market is in its early stages, it is unclear whether there is enough hydrogen available to supply mass deployments of FCETs.

Similar to **Section II. FCET Commercialization Roadmap**, CALSTART conducted research to understand hydrogen markets and the drivers and barriers to this sector. As such, CALSTART completed a literature review of secondary sources from industry, U.S. governmental agencies, and academia to develop a roadmap for hydrogen infrastructure in California. CALSTART also interviewed hydrogen producers, hydrogen station developers, and hydrogen equipment manufacturers.[29]

Concerted action must be taken to advance the hydrogen production market and the MHD hydrogen fueling station market, especially in order to secure enough hydrogen

[29] See **Appendix I. Interview Methodology** for details about these interviews.

supplies to serve the FCET market and to build a hydrogen fueling network. CALSTART has determined three broad recommendations for state and federal government, financers, hydrogen producers, and hydrogen station developers to help accelerate the development of the hydrogen market:

1. Support in-state, low-carbon hydrogen production.
2. Develop a hydrogen fueling network.
3. Reduce the price of hydrogen.

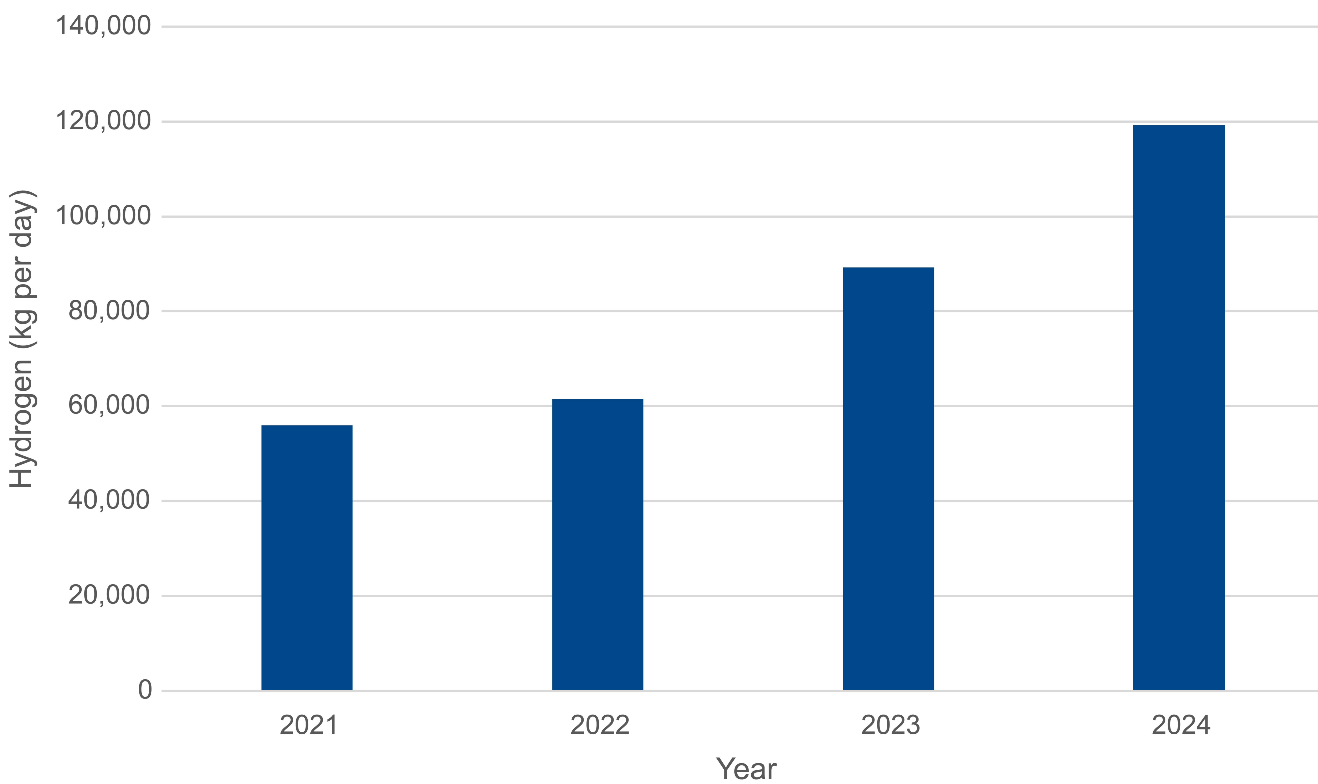
This section breaks down each recommendation into one or more action items and provides responsible entities and estimated costs to achieve each goal (when applicable). The resulting roadmap will help accelerate the hydrogen market in California and will be instrumental in advancing the industry to Phase 4 (Maturity) of commercialization, in which FCETs will be used in long-haul and all other feasible applications.

Support In-State, Low-Carbon Hydrogen Production

Hydrogen Production Capacity

FCET deployments will be constrained by hydrogen availability, which inhibits the size of the market. To quantify this constraint, CALSTART estimates that 61,500 kg per day of hydrogen is available to the transportation market in California as of 2022. CALSTART has identified additional hydrogen production projects that will be online in coming years, determining that the amount of available hydrogen in 2024 is estimated to be about 119,000 kg per day. These projections were made based on data gathered from the University of California Irvine's *Renewable Hydrogen Production Roadmap for California Report*. Data was also gathered from interviews with hydrogen producers. Most of the hydrogen producers interviewed provided data about short-term plans to deploy production capacity through 2024.[30] This information is displayed in Figure 11.

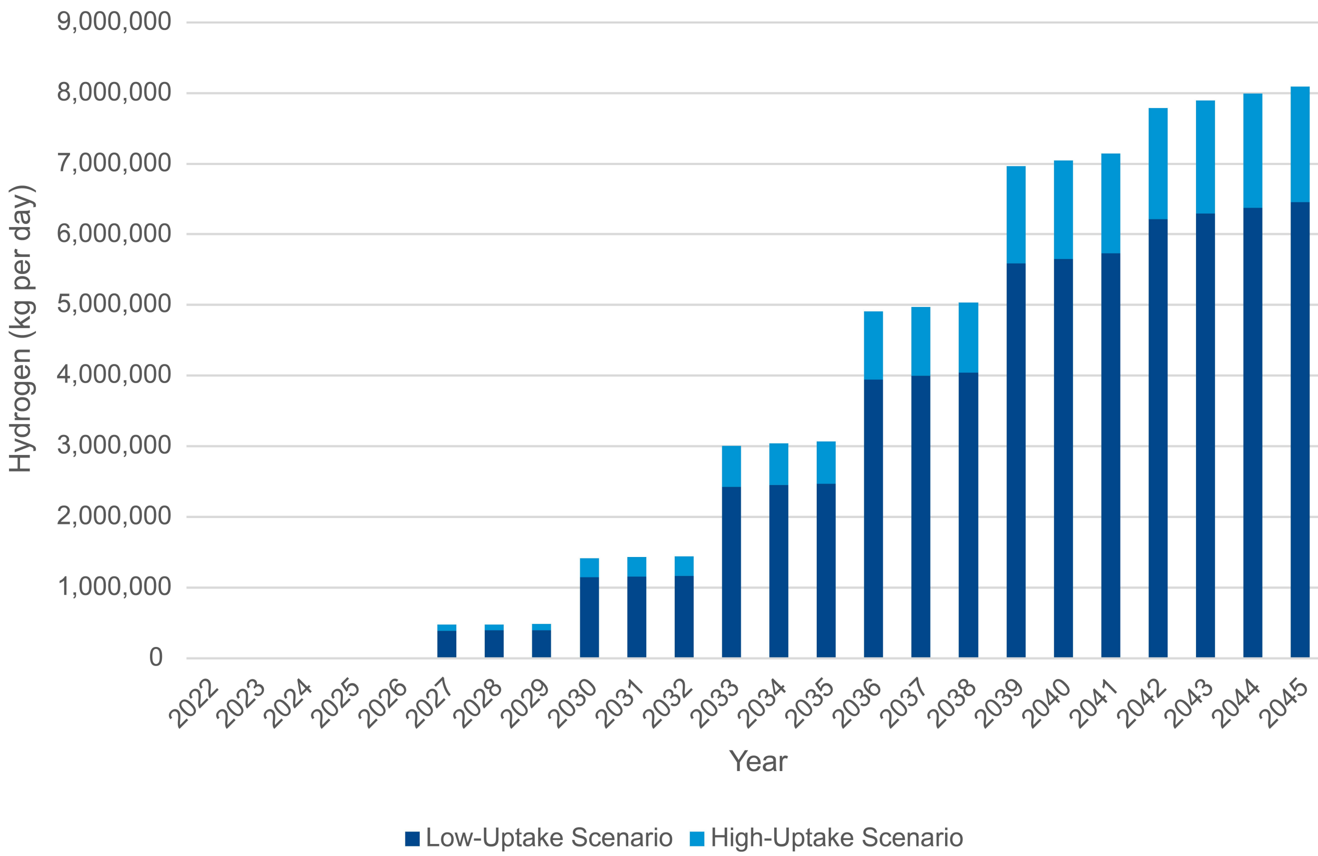
Figure 11. HD Hydrogen Production Capacity



[30] See **Appendix D. Hydrogen Production** for additional data source and methodology details.

The 2024 level of hydrogen production falls short of projected demand by 2045 under both the low-uptake scenario (6,457,665 kg per day) and the high-uptake scenario (8,092,963 kg per day) illustrated in Figure 12. Figure 12 shows projections for hydrogen demand for Class 8 FCETs only.[31]

Figure 12. Projected Hydrogen Demand for Class 8 FCETs



This lack of fuel will further limit FCET deployments. Developing production capacity means constructing more hydrogen production plants and/or further increasing production plant capacity, both within the state and in neighboring states near California's border. Production capacity could also be increased with onsite hydrogen production at fleet depots.

Low-Carbon Production Pathways

At the time of writing, the majority of hydrogen available to the California market is made from natural gas via steam methane reforming (SMR), which uses natural gas (of which methane is the main component) and steam as an input. The steam methane reformer

[31] Information from hydrogen producers beyond 2024 was extremely limited. The methodology for this analysis can be found in **Appendix F. Hydrogen Demand**.

combines natural gas with steam at a high temperature. A series of reactions using a catalyst creates end products of carbon dioxide (CO2) and hydrogen. Currently, SMR is the least expensive method of hydrogen production. However, natural gas is a fossil fuel, and this production method emits GHGs. The zero-emission transportation industry has therefore begun to investigate alternative low-carbon hydrogen production pathways to reduce life-cycle emissions.

Low-Carbon SMR Methods

There are several other hydrogen production pathways that can produce low-carbon hydrogen. One pathway is SMR with sequestration. Under this production pathway, SMR would occur, but CO2 released during the reforming process would be captured and prevented from escaping to the atmosphere. The captured CO2 can then be sold for use in industrial processes or sequestered in the ground.

An alternative approach to reduce the GHG footprint of SMR is using renewable natural gas as the feedstock (i.e., raw material). Renewable natural gas is produced by capturing the methane that arises when organic waste such as manure, compost, or food waste decomposes. Similar to fossil-based natural gas, the primary component is methane, a potent GHG. However, renewable natural gas is sourced from biotic material. As a result, the carbon had previously been in the atmosphere before it was sequestered, which means there is zero net effect in moving carbon from the ground to the atmosphere. In fact, in the ideal case, capturing methane from the decomposition of biomass could prevent methane from entering the atmosphere, thus having a beneficial effect on climate change. Renewable natural gas can be sourced from landfills, wastewater treatment plants, or agricultural waste sites.

Pyrolysis

Pyrolysis has also emerged as a potential hydrogen production method. Pyrolysis involves heating biomass in an oxygen-deprived environment. In this intense heat, the biomass starts to decompose but does not combust. The byproducts of this process are hydrogen, CO, CO2, and carbon black. Typically plant waste products are used as a feedstock for pyrolysis.

Electrolysis

Electrolysis is another production pathway that is being investigated to produce low-carbon hydrogen. Electrolysis involves using an electrical current to produce hydrogen. During this process, an electrical current is used in an electrolyzer to break down water into gaseous hydrogen and oxygen. This process, however, has major efficiency losses, meaning the amount of energy that can be recovered from consuming hydrogen is significantly less than the energy required to make it. Due to this efficiency loss, using grid power to produce hydrogen would be counterproductive as energy would be lost in the production process.

The use of renewable energy can facilitate electrolysis. Renewable energy sources often result in generating excess power, beyond what is demanded by customers on the grid. Grid operators respond to this situation by engaging in power curtailments. Power curtailments occur when the supply of electricity exceeds demand to the extent where it outstrips the grid's transmission ability, which happens frequently with renewable energy. During the middle of the day, energy production from solar panels ramps up; the amount of electricity produced exceeds demand, leaving electricity that cannot be used immediately. Later in the day, electricity production from solar panels ramps down as solar irradiation decreases; this occurs as energy demand begins to increase.

The curtailed power generated during low demand is effectively wasted, but this problem can be addressed with energy storage, which saves energy for use when solar production decreases and demand increases. Lithium-ion batteries are the most cost-effective way for short-term, intra-day energy storage, but there is not currently enough battery storage to capture all of California's curtailed power.

Electrolysis could also be used to convert this curtailed power into hydrogen. Generally, electrolyzers are deployed to consume curtailed power. To do so, electrolyzers need to be located in areas where the grid has significant amounts of excess renewable energy power. Under this model, the electrolyzer would consume energy to produce hydrogen that would ordinarily be curtailed. California Independent System Operator (CAISO) is California's grid operator, and energy can be traded on CAISO's wholesale markets, which offers energy at wholesale prices. The price of curtailed power should theoretically be low given that the energy is not used. During times when there is excess renewable energy on the market, the price of energy decreases—there have even been cases when the price has been negative [CAISO, 2022]. However, electrolyzers are not eligible to trade on CAISO's markets and cannot access wholesale rates. Instead, energy for electrolyzers must be purchased from a utility. Utility rates are higher than wholesale rates, to the point where using an electrolyzer to make hydrogen is not economically feasible. CAISO granting electrolyzers access to these wholesale rates could allow electrolytic hydrogen to be more cost competitive.

Electrolyzers can also be attached to behind-the-meter (BTM) renewable energy. Under this scenario, an electrolyzer is connected to a renewable energy (solar or wind) plant that is dedicated to powering the electrolyzer. Instead of purchasing electricity from a utility, the electricity from the BTM plant is used to power electrolyzers.

Two major projects currently plan to use electrolyzers and renewable energy sources to produce electrolytic hydrogen in California:

- SoCal Gas's study "The Role of Clean Fuels and Gas Infrastructure in Achieving California's Net Zero Climate Goal" envisions that electrolytic hydrogen will be a part of California's energy portfolio. This study assumed that a significant portion of electrolyzers will be located in Eastern California. These electrolyzers will be co-located with BTM renewable energy projects, which minimizes electric transmission costs. Pipelines will then be used to transport hydrogen to market [SoCal Gas, 2021].
- The HyBuild Los Angeles, under the Green Hydrogen Coalition, aims to use curtailed power from renewables to produce hydrogen. HyBuild Los Angeles envisions that hydrogen will be produced via electrolysis powered by solar energy. The hydrogen produced will be transported to the Los Angeles basin via pipeline and used for transportation, industry, and power generation. This project's primary objective is to develop the first scaled ecosystem for green hydrogen in North America to attain $2.00 per kg for delivered green hydrogen in the Los Angeles basin [Green Hydrogen Coalition, n.d.].

The production potential for electrolytic hydrogen via curtailed power is explored in **Appendix E**.

Action Items

To reduce transportation-related GHG emissions, the trucking sector will need to use low-carbon hydrogen. There are multiple potential pathways for producing low-carbon hydrogen, but it is currently produced in small volumes. With demand for low-carbon hydrogen projected to increase, action will need to be taken to ramp up production. CALSTART recommends the following actions to meet this future market demand.

A. Leverage Funding for Low-Carbon Hydrogen Production

Seek Federal Funding for Low-Carbon Hydrogen Production

California should seek federal funding to produce low-carbon hydrogen. DOE has released a solicitation that will fund the creation of hydrogen hubs. This Regional Clean Hydrogen Hubs solicitation, which was funded by the Infrastructure Investment and Jobs Act (IIJA), devotes $8 billion to fund at least four hydrogen hubs that are expected to be dispersed across the country in different geographic regions.[32] IIJA lists several feedstocks that can be used to produce hydrogen in a hydrogen hub, which includes renewable energy, nuclear power, and fossil fuels & carbon capture and sequestration. At least one hydrogen hub that uses each feedstock must be funded. End uses for the produced hydrogen include transportation, residential and commercial heating, industrial sector, and power generation; there must be at least one hydrogen hub for each end use. CALSTART recommends that the State of California pursues funding from this solicitation to build and deploy a hydrogen hub that uses renewable energy to produce hydrogen for the transportation sector.

Support the Establishment of a State Fund to Finance Clean Hydrogen Production

Senate Bill (SB) 1075, introduced to the California Senate on February 15, 2022,[33] originally called for the creation of the California Clean Hydrogen Hub Fund within the I-Bank. This funding could have been used to provide grants for clean hydrogen projects in California; match or supplement federal funds granted to a regional clean hydrogen hub; or provide or match research funds for producing affordable hydrogen from renewable feedstocks. This bill would have also required the Governor to appoint a Clean Hydrogen Hub Director by April 1, 2023, to coordinate this effort. SB 1075 was ultimately amended. The amendments removed the provisions for creating the California Clean Hydrogen Hub Fund. The amended bill was then passed by the California legislature and became law on September 16, 2022.

The exclusion of the California Clean Hydrogen Hub Fund effectively removed a state funding mechanism for building out additional hydrogen production. A state fund for clean hydrogen production could help California become more competitive for IIJA's Hydrogen Hubs solicitation described in the above and could allow the state to continue to build this network of hydrogen hubs beyond what IIJA may cover. An alternative funding mechanism to support hydrogen production projects in California should be developed.

[32] For more information about IIJA, visit https://www.congress.gov/bill/117th-congress/house-bill/3684/text.

[33] For more information about SB 1075, visit https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202120220SB1075.

B. Fund Shovel-Ready Projects to Increase Renewable Hydrogen Production

Over the years, California has provided funding to produce renewable hydrogen. This hydrogen production capacity was included in the analysis shown in Figure 11. HD Hydrogen Production Capacity.

- In 2017, CEC issued GFO-17-602: Renewable Hydrogen Transportation Fuel Production Facilities and Systems. This solicitation aimed to fund renewable hydrogen production plants that can produce at least 1,000 kg per day. Funding was awarded to three production plants in 2018 [CEC, 2018]. These facilities have all been built.
- In April 2021, CEC provided more funding to build renewable hydrogen plants by issuing the Clean Transportation Program's GFO-20-609.[34] This solicitation provides grant funding to design, build, and operate a hydrogen facility that produces 100% renewable hydrogen for the transportation market. In February 2022, CEC announced awards for GFO-20-609, a total of $9 million in funding awarded to Linde, SG H2 Lancaster, and StratosFuel. This funding will support production facilities that can produce 17,728 kg of hydrogen per day. All of these facilities are scheduled to complete construction and commissioning by the end of 2023.

Six additional projects were listed as finalists under GFO-20-609. These projects received a passing score and are eligible for funding though they were not actually awarded. These six projects, if built out, would produce an additional 22,100 kg of hydrogen per day by 2025 (Table 6) and expand hydrogen production capacity for the transportation market by 17%—a major increase.

Table 6. Hydrogen Production Capacity with Unfunded GFO-20-609

Year	Hydrogen Production Capacity (kg per day)[35]	Hydrogen Production Capacity with Unfunded GFO-20-609 Projects (kg per day)
2022	61,500	61,500
2023	89,228	92,428
2024	119,228	138,828
2025	119,228	141,328

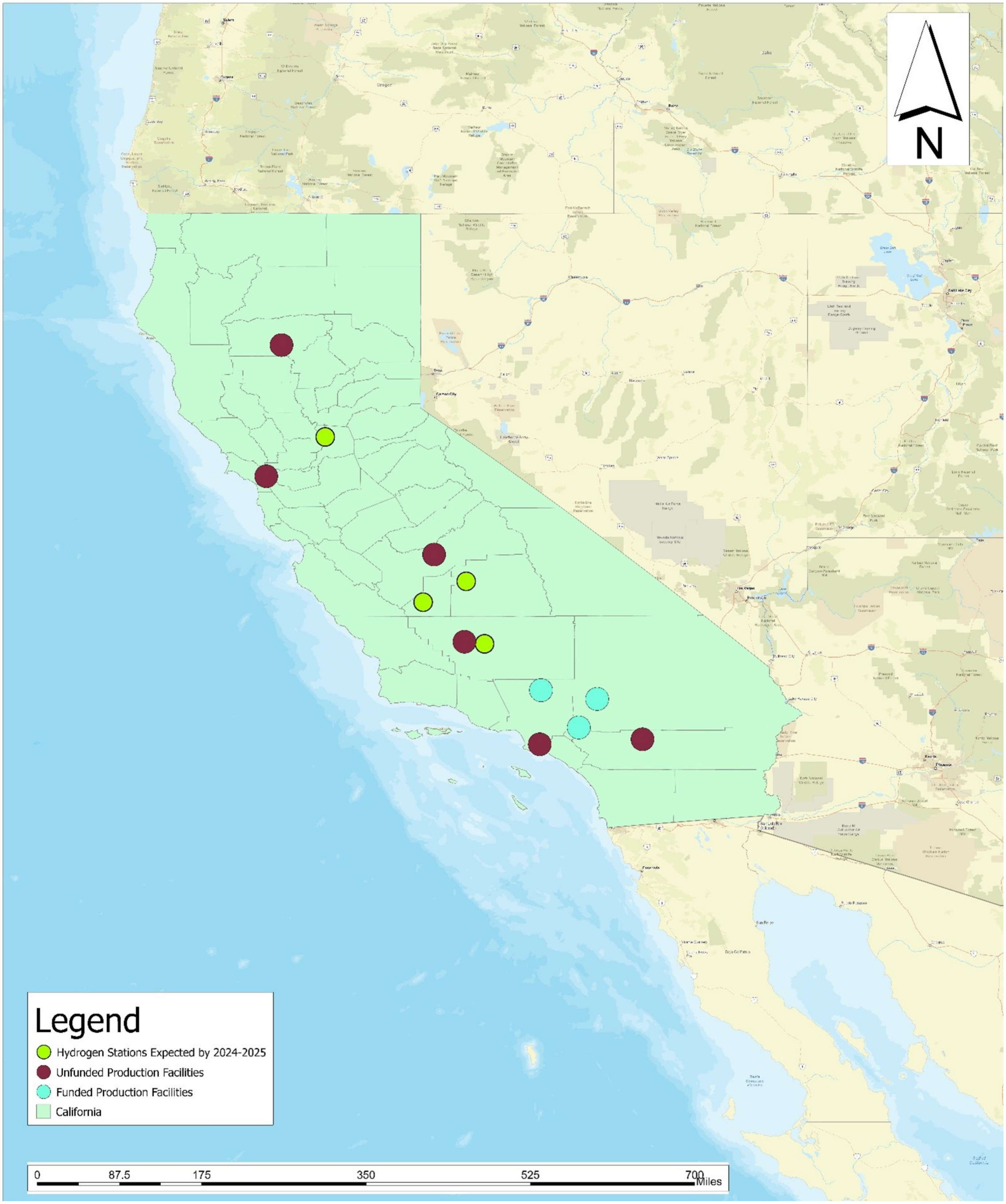
[34] For more information about GFO 20-609, visit https://www.energy.ca.gov/solicitations/2021-04/gfo-20-609-renewable-hydrogen-transportation-fuel-production.

[35] Includes production capacity of projects funded under GFO-20-609.

To increase hydrogen production, CEC could fund shovel-ready projects such as these six finalist projects. The amount of requested funds from these six projects totaled $17 million. This relatively small investment would greatly increase hydrogen production for California's market and ensure that hydrogen production is distributed throughout the state. This amount of funding represents a small portion of California's budget for clean transportation. By comparison, CEC plans to spend $20 million for hydrogen station maintenance plus $5 million on workforce development in FY2022–23 [CEC, 2022].

Figure 13 shows the approximate locations of the proposed projects. The three awarded projects are all located in Southern California. If funded, the other six projects would provide hydrogen production plants in the Bay Area and the Central Valley, which are both expected to be FCET hubs in the future. Geographical proximity affects the cost of distributing hydrogen and the ease with which retail fueling stations and fleets can access hydrogen. Many of these production plants are also located along trucking corridors. The State of California should ensure that funded hydrogen production projects are in geographically diverse areas within California so that hydrogen can be easily distributed in all parts of the state.

Figure 13. Awarded and Un-Awarded GFO-20-609 Projects



While these six projects could greatly increase the production and distribution capacity for hydrogen throughout the state, the amount of hydrogen produced by these projects would not fulfill expected demand for hydrogen. By 2045, hydrogen demand for the HD FCET market is expected to be between 902,000 to 3,204,000 kg per day. (Expected hydrogen demand is discussed in full in the next recommendation: **Develop a Hydrogen Fueling Network**.) As a result, hydrogen production will need to increase rapidly to meet this demand. Based on the projected costs identified in the proposals submitted to GFO-20-609, producing enough hydrogen to meet 6,457,665 kg per day of demand would require about $40.5 billion in investment. To meet 8,092,963 kg per day of demand would require about $51 billion in investment. These figures are based on current hydrogen production facility costs and do not take into account inflation or potential price decreases due to economies of scale.[36] Scaling up hydrogen production to meet projected demand would require the mobilization of private investment.

C. Fund Research for Other Low-Carbon Hydrogen Production Methods

While electrolytic hydrogen is promising to meet demand, other forms of low-carbon hydrogen production can become economically viable. CEC has previously issued solicitations like GFO-21-502, which funded projects that demonstrate new technologies and processes for producing low-carbon hydrogen. Electrolysis and fossil-fuel hydrogen pathways were not eligible for funding under this solicitation as it was intended to fund new processes/technologies.

This solicitation funded two classes of projects: pilot demonstrations and advancing readiness of emerging technologies. The four projects funded totaled $4 million:

- Catalytic Dry Reforming of Biogas to Hydrogen
- Catalytic Non-Thermal Plasma Biogas to Hydrogen
- Direct Solar Conversion of Biogas to Hydrogen and Solid Carbon
- Renewable Hydrogen Generation from Organic Wastes via Microbial Electrolysis

California should continue to pursue research into new hydrogen production technologies and processes and issue solicitations similar GFO-21-502 to explore promising low-carbon hydrogen production pathways and ensure future hydrogen demand can be met with utmost efficiency and cost effectiveness.

[36] The methodology for these calculations can be found in **Appendix D. Hydrogen Production**.

Develop a Hydrogen Fueling Network

As discussed above, an adequate supply of hydrogen will be necessary to enable FCET market commercialization. But hydrogen production is only one of the constraints Class 8 FCETs face—hydrogen fueling station capacity must also be addressed. If there is insufficient station capacity, only a portion of produced hydrogen can be dispensed.

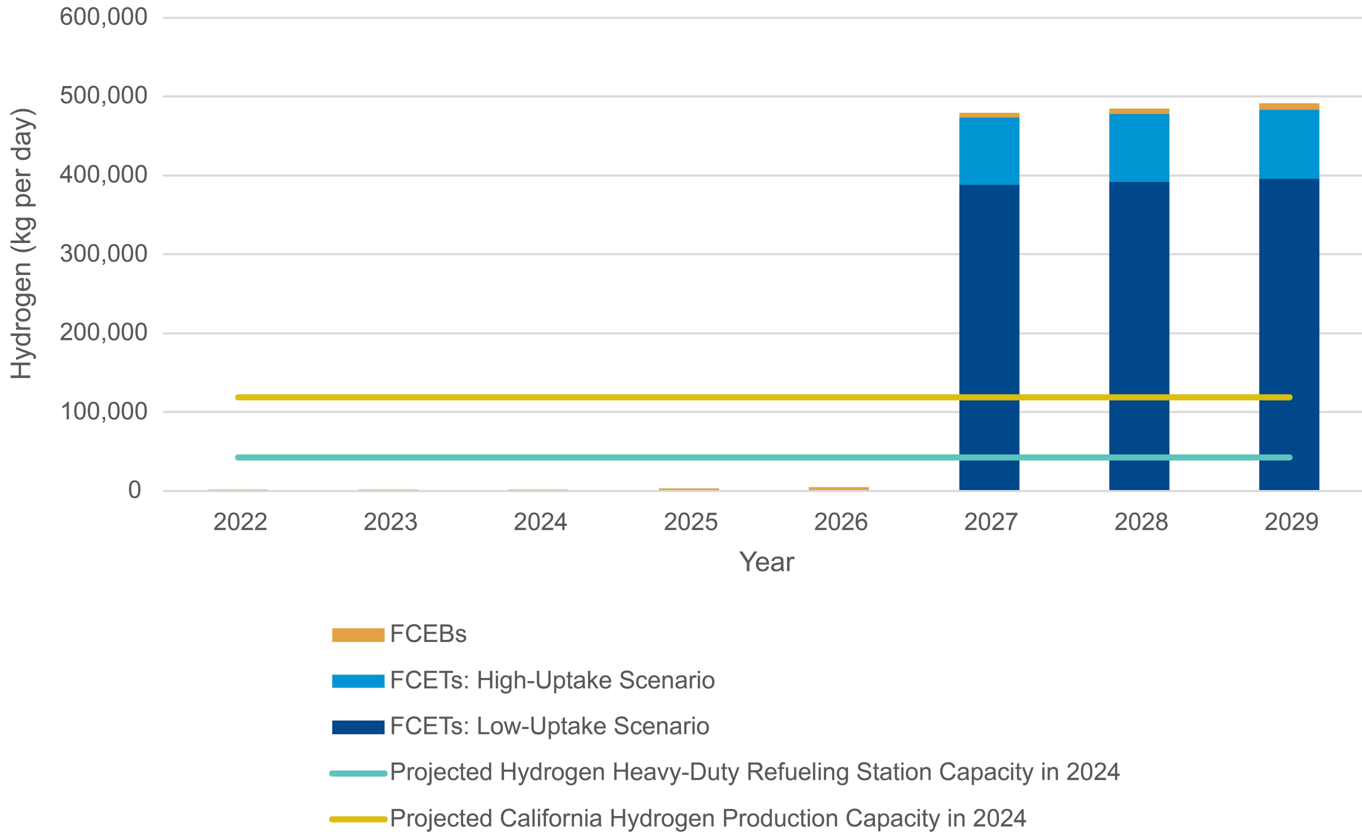
Current light-duty stations do not have enough storage capacity to fuel FCETs at scale, and standards for light-duty fueling are generally not compatible with HD FCETs [Hydrogen Fuel Cell Partnership, 2019]. For example, a light-duty station will not expect to dispense the volume of hydrogen that HD trucks require. A high-volume request may cause the light-duty station to terminate fueling, as the system may consider this volume to be a leak in the tank or some other fault. At the time of writing, there are four HD hydrogen fueling stations in operation, and these stations currently have low-volume capacity. The largest planned fueling station in California will have about 6,000 kg per day capacity, but the stations in operation today are below 2,000 kg per day.[37] As will be shown below, hydrogen fueling station capacity must increase along with production to meet projected demand.

From interviews for this project with fueling providers and while conducting secondary research, CALSTART learned of plans for MHD hydrogen fueling stations through 2024. Figure 12 previously showed projections for hydrogen demand for Class 8 FCETs only. Figure 14 below shows projections for hydrogen production and hydrogen fueling station dispensing capacity. These projections compare hydrogen fueling station capacity expected to exist by 2024 and the amount of produced hydrogen that cannot be dispensed due to lack of fueling station capacity. Figure 14 projects hydrogen demand from both FCETs and FCEBs.[38]

[37] Based on data gathered from interviews with hydrogen retail stations and hydrogen stations awarded through CEC solicitations and the EnergIIZE program.

[38] The methodology for this analysis can be found in **Appendix F. Hydrogen Demand**.

Figure 14. Projected Hydrogen Demand for Class 8 FCETs



Based on this analysis, hydrogen demand will quickly exceed projected fueling station capacity and hydrogen production capacity by 2027 even in the low-adoption scenario. Without an increase in both hydrogen production plants/capacity (see the **Support In-State Low-Carbon Hydrogen Production** section) and hydrogen fueling station capacity to dispense produced fuel, a major shortfall of hydrogen will occur soon.

Action Items

During earlier stages of commercialization, the vast majority of FCETs are expected to be used for drayage and regional haul applications, but once later stages (Phases 3 and 4) are reached, FCETs are expected to serve long-haul routes. These applications would require hydrogen fueling corridors for refueling over longer trips. The resulting fueling corridor network would be akin to the current network of truck stops. The steps outlined below are critical to successfully deploy a hydrogen fueling network.

A. Apply for Hydrogen Fueling Station Funding

There are currently two programs that CALSTART recommends the State of California pursue to secure funding for HD hydrogen fueling stations.

EnergIIZE Commercial Vehicles Project

Launched by CEC and managed by CALSTART, the EnergIIZE Commercial Vehicles Project provides funding to entities to help finance the purchase of charging and hydrogen infrastructure. EnergIIZE funds MHD infrastructure and is intended to primarily benefit communities with disproportionately high levels of air pollution. EnergIIZE covers only part of the infrastructure hardware and software costs. For hydrogen projects, equipment that is eligible for funding includes compressors, liquid and gaseous pumps, piping and pipelines, hydrogen dispensers with hoses and nozzles, high-pressure storage, onsite production equipment, chillers, switchgear, electrical panel upgrades, wiring and conduit, and meters. (Construction, labor, and utility upgrade costs are not eligible for funding under this program.)

State funding for HD hydrogen stations will primarily be allocated through EnergIIZE. EnergIIZE will fund 50% of the equipment cost of a hydrogen station, up to $3 million ($4 million for disadvantaged communities). EnergIIZE can be used to fund private or public stations.

In 2022, EnergIIZE had a budget of $69 million for both charging infrastructure and hydrogen stations. Approximately $17 million was allocated for public MHD truck hydrogen stations. These stations funded by EnergIIZE are expected to be online by 2024 and will collectively have a fueling capacity of approximately 21,000 kg per day, marking a significant increase in hydrogen fueling capacity. EnergIIZE's budget is expected to increase over time, and in future years 30% of the budget will be allocated to hydrogen. As a result, there could be an increase in funding for HD stations in the future.

In the short term, EnergIIZE can help to support FCET commercialization. To advance commercialization from Phase 2 (Development) to Phase 3 (Growth), 500–900 FCETs will need to be deployed. Based on a duty cycle of 300 miles per day, this number of trucks equates to hydrogen refueling capacity of approximately 24,000–44,000 kg per day of dispensing capacity. Based on the analysis of stations funded by the State of California, there will be enough hydrogen refueling capacity by 2024 to meet this demand. The decision to build out the fueling network ahead of the FCET market will help to facilitate early FCET deployments. However, the hydrogen fueling infrastructure network will need further development to meet projected demand. EnergIIZE funding can be used to continue to expand refueling capacity to prepare the market for mass FCET adoption.

IIJA Alternative Fuels Corridors Funding

Section 1413 of the FAST Act mandated that the U.S. Department of Transportation (DOT) designate corridors for EV charging and hydrogen, propane, and natural gas fueling. In addition, DOT was mandated to investigate the short-term and long-term need for charging and fueling infrastructure. This task fell under the jurisdiction of the Federal Highway Administration (FHWA), which established an Alternative Fuels Corridors (AFC) program. Under the AFC program, FHWA accepts input from state departments of transportation to designate a national AFC network. FHWA has designated several interstate highways and U.S. routes/state highways as AFCs.

The passage of IIJA provided funding to build and install EV charging and fueling for hydrogen, propane, and natural gas. The AFC funding through IIJA totals $7.5 billion, which is to be distributed through several programs. The National Electric Vehicle Infrastructure (NEVI) Formula Program was allocated $5 billion to help states build out AFCs. NEVI, however, only allocates funding for EV infrastructure.

Hydrogen is eligible for AFC funding through two other grant programs:

- Corridor Charging Grant Program ($1.25 billion) will deploy public EV charging and fueling infrastructure for hydrogen, propane, or natural gas along AFCs.
- Community Charging Grant Program ($1.25 billion) will deploy public EV charging and fueling infrastructure for hydrogen, propane, or natural gas in communities [FHWA, 2022].

To be eligible for funding through these programs, the hydrogen infrastructure needs to be deployed along a designated FHWA AFC. To be considered complete, an AFC would require no more than 150 miles between public hydrogen stations on the corridor and that such stations be located no more than five miles away from freeway exits or highway intersections [FHWA, 2022a].

B. Allocate Resources to Build Retails Stations in First-Mover Clusters

Since most FCETs will first be used for drayage and regional-haul duty cycles, clusters of FCET deployments will be developed first: Los Angeles-Orange County-Inland Empire, the Bay Area, the Central Valley, and San Diego. Initial demand for hydrogen will therefore be greatest in these areas and will likely be most attractive for deploying retail fueling stations. Resources should be prioritized for building a hydrogen fueling network in the four clusters described below (Table 7).[39] Developing these clusters is vital to advancing commercialization to Phase 3 (Growth).

Table 7. Goods Movement Clusters for Hydrogen Fueling Station Deployment

Cluster	Estimated Fueling Capacity by 2024 (kg per day)	Estimated Demand by 2030 (kg per day): Low-Uptake Scenario	Estimated Demand by 2030 (kg per day): High-Uptake Scenario	Estimated Number of Additional Hydrogen Fueling Stations Required by 2030
Los Angeles-Orange County-Inland Empire	23,500	64,200	175,650	9–31
Bay Area	3,200	5,725	29,350	1–6
Central Valley/SR-99	15,650	41,900	103,700	6–18
San Diego	0	2,800	11,900	1–3

While there have been some early hydrogen station deployments, additional hydrogen stations will need to be deployed in these clusters to meet projected demand. Since there are few FCETs currently on the road, there is an opportunity to deploy hydrogen stations ahead of FCET deployments. Programs like EnergIIZE can be used to provide funding to build out the hydrogen infrastructure network.

These figures include only hydrogen demand for vehicles that are based in these clusters. Since these clusters are major generators of freight traffic, FCETs originating from outside of the cluster will need to fuel. As a result, the estimated hydrogen demand should be viewed as the minimum requirements for each cluster.

[39] See **Appendix G. First-Mover Clusters** for the methodology used to determine these clusters and develop kg per day estimates.

Los Angeles-Orange County-Inland Empire Cluster

Class 8 trucks are used to provide drayage service from the Ports of Los Angeles and Long Beach. Combined, these two ports process 31% of all containerized international waterborne trade in the United States. Many of these trucks use the Interstate corridor I-710 and I-110, as well as State Route (SR) 60 and I-10 freeways, to transport cargo to and from the ports, railroads, and warehouses in the surrounding cities. HD hydrogen fueling stations should therefore be established in the following locations:

- Ports of Los Angeles and Long Beach: There will be a high concentration of FCETs picking up and dropping off cargo at these two ports.
- Ontario/Riverside: The Ontario/Riverside area hosts a large concentration of warehouses. These warehouses are the destination for much of the cargo arriving at the Ports of Los Angeles and Long Beach.
- Commerce: Commerce hosts the BNSF Railway and the Union Pacific Railroad. Since many trucks from the ports currently deliver cargo to these railways, there will be a high concentration of FCETs in this area.
- I-710 Corridor: Trucks use I-710 heavily to transport goods from the ports to the rail stations in Commerce or to warehouses in the Ontario/Riverside area. As FCETs are deployed, they will need refueling stations along this route. It is important to note that I-710 is already a designated FHWA AFC and could also receive IIJA AFC funding to build hydrogen fueling infrastructure.
- SR-60 and I-10: Trucks use these freeways to run east-west routes. These freeways are used heavily by trucks travelling to the Ontario/Riverside area. As FCETs are deployed, they will need refueling stations along this route. Both I-10 and SR-60 are already listed as AFCs by FHWA and could also receive IIJA AFC funding to build hydrogen infrastructure.

Building a hydrogen network in the Los Angeles-Orange County-Inland Empire cluster should be a priority because most of the hydrogen demand in California will come from this area. So far, this cluster has been the main focus of efforts to deploy hydrogen fueling infrastructure.

Bay Area Cluster

Much of the goods movement in the Bay Area is connected to the Port of Oakland. Many of the goods from the Port of Oakland remain in the Bay Area, which includes Alameda, Solano, Napa, Sonoma, Marin, San Francisco, San Mateo, San Clara, and Contra Costa counties. I-880, I-80, I-580, U.S. 101, I-680, SR-12/37, SR-152, and SR-4 are common corridors that trucks use to transport goods [Metropolitan Transportation Commission, 2016]. The following locations currently experience a high volume of goods movement and will see high concentrations of future FCET deployments, meaning they should be considered prime locations for hydrogen fueling stations:

- The Port of Oakland is the point of entry for most of the Bay Area's cargo.
- The Oakland International Airport is the point of entry for air cargo.
- The I-880 corridor serves most of the Bay Area's industrial area.
- The San Leandro and San Jose areas each have a large concentration of warehouses.

Central Valley/SR-99 Cluster

The Central Valley is a major cluster for California's trucking industry. The area receives freight from the Bay Area and has several cities that produce their own trucking trips. The Fresno Council of Governments commissioned a study that identifies major freight hubs within the Central Valley. The following locations are some of the areas in the Central Valley that were identified in this study as having major freight activity [Cambridge Systematics, 2017]:

- The cities of Tracy and Lathrop contain distribution centers connected to Bay Area ports, including an Amazon fulfillment center. These cities are also considered to be the Central Valley's gateway to the Bay Area.
- Sacramento has the Port of Sacramento and hosts intermodal rail lines. The Port of Sacramento is also currently hosting a fuel cell locomotive demonstration project [ACT News, 2022].
- Stockton has the Port of Stockton and intermodal rail lines, as well as multiple distribution centers.
- Modesto is home to large agriculture businesses, an intermodal facility, and a distribution facility.
- Fresno hosts several distribution centers, agricultural businesses, and an airport. Fresno also has an intermodal facility that connects rail and trucks. As a result, Fresno is a major logistics hub in the Central Valley.
- Bakersfield has numerous distribution centers and logistics companies. These companies serve the agriculture, mining, manufacturing, and retail trade sectors. Bakersfield also has access to multiple freeways, including CA-65 and CA-58, and is in proximity to I-5. It is considered the gateway into the Los Angeles basin.

Each of the cities named above should be considered prime locations for HD hydrogen fueling stations. Taken collectively, all of these locations would form a corridor along I-99. Building these fueling stations in each cluster would also help to facilitate long-haul trucking in the future. I-99 is designated as an FHWA AFC and could also be funded with IIJA AFC funding.

San Diego Cluster

The Port of San Diego consists of two terminals: the 10th Avenue terminal primarily handles refrigerated containers for agricultural products and bulk goods (i.e., goods that do not fit into shipping containers) and the National City terminal primarily handles new cars and imported vehicles. The Port of San Diego's freight is largely moved to its destination via truck. This freight has a variety of destinations. Some of this freight remains in the San Diego region. Goods that remain in the San Diego region are typically transported to Otay Mesa [Port of San Diego, 2021]. To serve the Port of San Diego, the following locations should be prioritized for building HD hydrogen fueling stations:

- 10th Avenue Terminal: Most goods that can be transported by conventional trucks arrive at the 10th Avenue Terminal, and there is a large concentration of truck drivers at this facility.
- Otay Mesa: Otay Mesa is a community along the border between the United States and Mexico. Some of the agricultural goods that arrive at the Port of San Diego are sent to Otay Mesa for processing before being shipped to Los Angeles, resulting in a large concentration of trucks.

C. Build Out Hydrogen Fueling Corridors

Many of the trucks operating in each of these four clusters primarily stay within their region of origin, and most trucks stay within their own county. However, there is a significant amount of long-haul goods movement outside of these clusters that are destined for other locations in California or even out of state. Goods transported to places outside of the clusters travel along several interstate and intrastate corridors. These corridors are ideal candidates for funding under the Corridor Charging Grant Program given that they form along corridors that have already been designated as AFCs by FHWA. Potential hydrogen fueling station locations, chosen using truck volume data,[40] are outlined in Figure 15. Building out these corridors is vital for facilitating the use of FCETs beyond regional-haul

[40] See FAF truck volumes data at https://ops.fhwa.dot.gov/freight/freight_analysis/faf/faf_truck_volumes_2017/Estimated%20Average%20Daily%20FAF%20Truck%20Volume%20(1_All%20Commodities)%202017.pdf.

applications and into long-haul applications, an important step for advancing commercialization to Phase 4 (Maturity).

Figure 15. First-Mover Clusters and Potential Hydrogen Fueling Corridors

Locations were also chosen so that stations would be no more than 150 miles apart, ensuring the corridors could be considered an AFC under IIJA. (Although trucks are expected to transport goods beyond California, this analysis is restricted to the state's borders.) While deploying fueling stations in clusters is the more immediate concern, over time hydrogen stations will need to be built out in the locations identified below to facilitate long-haul trucking.

- **I-8 Corridor:** While some freight arriving at the Port of San Diego is transported to regional destinations, the majority of the freight is transported outside of the San Diego area. The Port of San Diego handles bauxite shipments. Some of this freight is destined for Tucson, AZ, and is transported along the I-8 corridor [Port of San Diego, 2021]. Potential locations for hydrogen fueling stations to facilitate goods movement include:
    - El Cajon: El Cajon is the last major town before entering the Low Desert. El Cajon has a concentration of warehouses and trucking companies and would be an attractive place to install hydrogen stations.
    - El Centro: El Centro is a town on the border with Mexico. This town has a concentration of warehouses and trucking companies and could therefore be a good market for hydrogen.
    - California-Arizona border: Tucson is about 240 miles away from the California-Arizona border, so this station is needed to facilitate a corridor into Arizona. Additional fueling stations will need to be built in Arizona to support this corridor.
- **I-15 Corridor to Las Vegas:** Goods from the Port of San Diego are also transported to Victorville and the High Desert region through this corridor, especially imports of bauxite and other dry bulk goods. Some goods continue past this region to Las Vegas and beyond [Port of San Diego, 2021]. I-15 can also facilitate goods movement from the Ports of Los Angeles/Long Beach and the Port of San Diego to Utah. Agricultural products from the Central Valley are also transported along this corridor (using SR-58 to connect to I-15) to Las Vegas and Utah [Braceras and Kuhn, 2017]. Establishing a fueling corridor along I-15 would help to facilitate the use of FCETs. The following locations are potential sites for hydrogen fueling stations:
    - Temecula/Escondido area: This area would provide a hydrogen fueling location for trucks traveling between San Diego and the Riverside/San Bernardino region.

    - Riverside/San Bernardino: There will likely be a large number of stations in this area to service the Los Angeles-Orange County-Inland Empire cluster. Trucks traveling along this route can take advantage of these stations.
    - Victorville/High Desert region: Victorville is a destination for freight from the Port of San Diego.
    - Barstow: Barstow is a major truck stop enroute to Las Vegas.
    - California-Nevada border: The distance between Barstow and Las Vegas exceeds 150 miles. An additional station will need to be built at the California-Nevada border to ensure that FCETs can access at least one station every 150 miles. This station can also help to facilitate the continuation of a hydrogen corridor into Nevada.
- **I-5 Corridor:** The I-5 freeway runs from the California-Mexico border to the Washington-Canada border. Within California, I-5 is a major artery for north-south traffic and a critical trucking route, running through the San Diego, Los Angeles-Orange County-Inland Empire, and Central Valley clusters. It is also near the Bay Area cluster and is accessible to trucking from this region. As a result, it plays a major role connecting the trucking clusters examined in this report. Furthermore, I-5 is a major route for all freight that is sent to Northern California. I-5 will be vital for long-haul, hydrogen-powered trucking. While many stations in this corridor will have been built to address cluster demand, other locations will still be needed:
    - Port of San Diego: The Port of San Diego is a major entry point for freight. Trucks can use stations built for the San Diego cluster.
    - Los Angeles-Orange County-Inland Empire cluster: The Los Angeles-Orange County-Inland Empire cluster is within 150 miles of San Diego. Trucks travelling along I-5 can use stations in the Los Angeles-Orange County-Inland Empire cluster.
    - Gorman: The Grapevine, which is the mountain pass between Los Angeles and the Central Valley, has a rigorous duty cycle. A station should be established between Los Angeles and Bakersfield. Gorman is a widely used rest stop for trucks passing through the Grapevine.
    - Sacramento-Stockton-Tracy: Trucks travelling along I-5 can use stations in the Central Valley cluster.
    - Redding/Shasta: Redding is the next major city north of Sacramento and should offer fueling stations for FCETs.

- California-Oregon border: A fueling station near the California-Oregon border would help facilitate the continuation of a hydrogen fueling corridor into Oregon.

- **I-10 Corridor:** The I-10 freeway is a major east-west corridor. This corridor runs from Los Angeles to Jacksonville, FL, and is important to the economy of the American Southwest. I-10 connects the Port of Los Angeles to the Inland Empire region, making it a major connector within the Los Angeles-Orange County-Inland Empire cluster. I-10 also connects Los Angeles to several major economic centers like Phoenix. In fact, the Los Angeles to Phoenix freight corridor is within the top 25 freight corridors in the United States by freight value. In addition, I-10 connects Los Angeles to major ports like Houston, TX [Rutter et al., 2019]. Due to the economic importance of this route, it is vital that a network of hydrogen refueling stations be deployed so FCETs can use it. The following locations are potential sites for hydrogen refueling stations:
  - Coachella Valley: The Coachella Valley is the first major populated area east of the Los Angeles-Orange County-Inland Empire cluster. The Coachella Valley already serves the trucking industry and has multiple trucking facilities like truck stops and truck fueling stations.
  - California-Arizona border: Phoenix, AZ, which is the next major destination along I-10, is approximately 270 miles away from the Coachella Valley. To provide an intermediate fueling option between these two locations, a fueling station should be built near the California-Arizona border.

- **I-40 Corridor:** The I-40 freeway is a major east-west corridor. It starts in Barstow at the junction with I-15 and travels eastwards toward Needles, CA. The I-40 freeway then continues east and eventually ends at Wilmington, SC. I-40 connects California with destinations like Flagstaff, AZ, and Albuquerque, NM. Since the portion of I-40 in California is relatively short, the following locations are potential sites for hydrogen refueling stations:
  - Barstow: Barstow marks the beginning of the I-40 freeway in California. Barstow is also a major hub for truck traffic as it is the junction of I-15, I-40, and SR-58 freeways.
  - California-Arizona border: The California-Arizona border is approximately 150 miles away from Barstow, and the next major city is in Flagstaff, AZ, which is another 200 miles beyond the border. A hydrogen station at this location could act as an intermediate fueling stop along this route.

- **I-80 Corridor:** The I-80 freeway is a major east-west corridor that runs from the Bay Area to the Central Valley and Sierra Nevada mountains to the California-Nevada border. This corridor provides the Bay Area with a direct route to Sacramento, making I-80 an important route for regional transportation and connecting the Bay Area and Central Valley clusters. However, I-80 also connects the Bay Area with other out-of-state destinations like Reno, NV, and other destinations to the east [Metropolitan Transportation Commission, 2016]. Sacramento is a potential site for hydrogen refueling stations on this corridor:
    - Sacramento: Sacramento is a major logistics hub—it hosts a port and a rail line and connects with the I-5 corridor. In addition, Sacramento is a freight destination for regional travel along I-80. Installing a hydrogen refueling station in Sacramento or the surrounding region would supply hydrogen for trucks providing regional service or service to Reno, NV. Sacramento is located approximately 140 miles away from Reno. A fueling station in this location would provide trucks with an intermediate fueling location between the Bay Area and Reno.

MHD stations are already planned for deployment along some of these corridors, particularly in the southern part of the Central Valley along the I-5 corridors and on SR-99. A station is also planned in the Sacramento region, which can help to serve traffic along I-5, SR-99, and I-80. These stations are expected to be deployed by 2024–2025.

D. Extend Hydrogen Refueling Infrastructure Credit Program to HD Stations

The FCEV industry suffers from a vicious cycle that has hindered the development of a hydrogen fueling network: fleets will not buy hydrogen-powered vehicles until a hydrogen network is in place to serve their vehicles. However, hydrogen providers will not build retail stations until enough vehicles are on the road to ensure stations will be profitable. To address this problem, the fueling network must be constructed first so that fleets will purchase FCETs.

California has incentivized the build-out of a hydrogen station network for light-duty FCEVs through Hydrogen Refueling Infrastructure (HRI) credits as part of the Low Carbon Fuel Standard (LCFS) credits program. Under this program, HRI credits help to compensate the owner for the risks of opening a hydrogen fueling station: when a station is built, there is a chance that it will not immediately sell enough hydrogen to be financially self-sufficient, and it is likely that much of hydrogen available at the station will not be dispensed due to current low demand. HRI credits are then awarded based on the difference between how much fueling capacity a station has and how much hydrogen it sells. As the station sells more of its dispensing capacity, it will earn more LCFS credits and fewer HRI credits.

To be eligible for HRI credits, a station must be open to the public (ideally 24/7), accept major credit/debit cards for payment, and not be directly related to a California Environmental Quality Act mitigation measure or California/federal settlement. However, regardless of the station capacity, HRI credits can only be awarded up to 1,200 kg per day max capacity, meaning the station can earn no more than 1,200 kg per day of LCFS credits and HRI credits combined. This effectively creates a de facto limit on the amount of HRI credits that HD stations can earn [CARB, 2021b]. As such, the current HRI credit program can provide only limited benefits to HD stations, depriving owners of an important incentive to build out hydrogen stations for FCETs. The HRI credit program should be extended to HD stations, especially since there are even fewer HD FCETs deployed than light-duty at the time of writing. Since FCETs consume more hydrogen than light-duty vehicles, the maximum station capacity eligible for HRI credits will need to also be increased for HD stations. CALSTART recommends increasing the maximum station capacity to 5,000 kg per day so HD stations can take full advantage of HRI credits.

E. Establish a Station Testing Program to Accelerate Station Commissioning

Station commissioning is a potential bottleneck to the deployment of hydrogen fueling stations. Before the station can be used by the public, it must go through a commissioning process to ensure that it functions in a safe manner and that it complies with fueling protocol standards. Previously, the commissioning process involved physically taking vehicles to hydrogen stations to complete fills so each OEM could validate the station's performance with their specific vehicle. Since each of these tests can take one to two weeks, the commissioning process is lengthy and can be especially problematic if a large number of stations need to be deployed in a short amount of time. To address this issue, Sandia National Laboratories and NREL developed the Hydrogen Station Equipment Performance device (HyStEP). HyStEP consists of hydrogen tanks that simulate the onboard storage tanks on a vehicle. During the commissioning process, hydrogen from the station is filled into HyStEP in place of the actual vehicle. This device had to be designed so that test fills into HyStEP would achieve the same results as fills into an actual vehicle. This required substantial collaboration with industry [Koning, 2016].

HyStEP was ultimately developed and is now used to commission light-duty hydrogen stations. However, there is no HyStEP equivalent for HD fueling or fast-flow HD fueling. Since multiple retail MHD hydrogen stations need to be deployed rapidly to support the FCET market, there is a risk that commissioning can be a barrier to the rollout of a hydrogen fueling network. Developing a HyStEP equivalent for MHD stations can accelerate hydrogen station deployments by addressing this barrier.

While recognizing that technologies and standards are still under development for MHD stations, it is important to plan accordingly and continue to build on the momentum to support the advancement of MHD-station deployments. There is significant knowledge and best practices learned from CARB's currently established hydrogen fueling station validation program for light-duty that can help accelerate station commissioning and ensure safe and reliable station operation. CARB is considering funding the development of a HyStEP 2.0 device that will have increased functionality compared to the original. However, since there is no HyStEP-equivalent device for HD fueling or high-flow HD fueling, CARB's hydrogen fueling station validation program should expand to include MHD stations. CARB, CEC, and/or NREL should develop the next-generation HyStEP 3.0 device to validate MHD fueling stations.

F. Develop Testing for Measurement Standards for MHD Hydrogen Stations

As part of the commissioning process and before a station can be used by the public, it must also comply with the California Department of Food and Agriculture's Division of Measurement Standards (DMS), which establishes and regulates the specifications and tolerances for commercial fuel dispensers and oversees the advertising, labeling, and method of sale requirements for all motor vehicle fuels sold in the state. Stations must comply with the hydrogen fuel quality standard, have all weighing and measuring devices installed for commercial purposes be type-approved, and meet the point-of-sale requirements. This applies to all hydrogen fueling stations installed for commercial purposes, regardless of weight class vehicles (light-duty and MHD). DMS currently ensures that stations meet the requirements through testing and dispenser-type evaluations using a dedicated test equipment/device. If a device manufacturer requires test parameters that exceed current equipment capabilities, it is incumbent upon the manufacturer to supply such equipment to facilitate type-evaluation. The type-evaluation can be done onsite at a manufacturers facility when necessary to accommodate type testing, but having an in-house, California device is more efficient and needed to expediate the commissioning process. Currently, there is no equivalent test equipment/device for MHD stations, and a larger tank and/or different test equipment will likely be needed for at least the annual dispenser inspections and testing.

Furthermore, in collaboration with CARB, DMS is currently considering adopting regulations that would require all hydrogen gas-measuring devices (dispensers) to maintain verification of testing that demonstrates conformance with SAE J2601.

Reduce the Price of Hydrogen

In interviews for this project, fleets identified the cost of hydrogen as a major barrier to adopting FCETs. Hydrogen is currently much more expensive than both diesel and the electricity that BETs consume. The price of hydrogen will need to reach parity with other fuels for FCETs to compete in the commercial vehicle market.

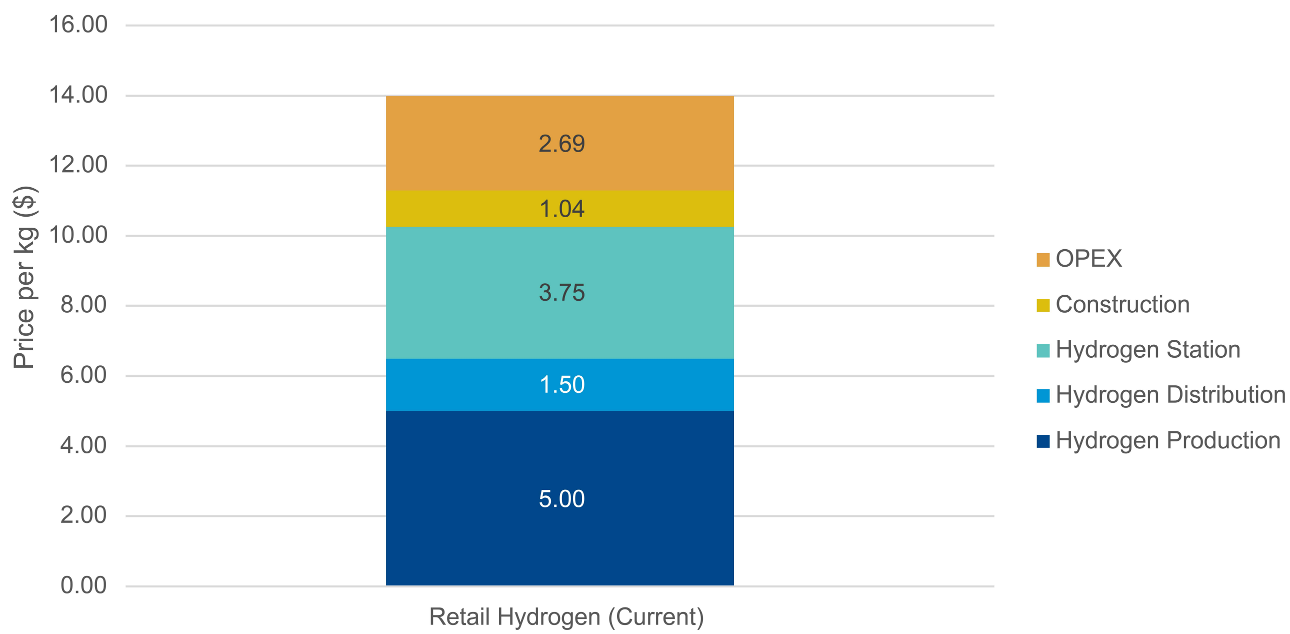
Current Retail Hydrogen Costs

Fleets have several options to obtain hydrogen fuel: purchasing hydrogen from a retail fueling station, which is akin to purchasing diesel at a fuel station, or building a station at their depot to either produce hydrogen onsite or have hydrogen delivered to refuel their trucks. Many fleets would like to fuel at their own depot, as onsite fueling would result in a cheaper cost per kg. In addition, fueling away from the depot requires labor and reduces the time that the trucks can be in operation. However, this option is not available for many fleets—a hydrogen station is expensive and requires a substantial capital investment. In addition, many fleets have a space-constrained depot and do not physically have room to install a hydrogen station. Many fleets also lease their depots and would require permission from the property owner to install a hydrogen station.

Therefore, most fleets will need to purchase hydrogen from retail hydrogen fueling stations. In addition to the factors described above, retail hydrogen stations will be necessary to facilitate long-haul and non-return to base operations. Currently, retail hydrogen is expensive compared to diesel. Market data indicates that the price of retail hydrogen as of December 2021 is $16.09 per kg. More than 70% of hydrogen stations sell at a price that exceeds $16 per kg. However, there are several liquid hydrogen stations that are selling hydrogen for approximately $13 per kg, so it appears that the current price of hydrogen ranges from approximately $13 to $16 per kg [CARB, 2021c]. However, during 2022, fuel prices increased significantly. Between January 2022 and June 2022, diesel prices increased by 55% [Bureau of Transportation Statistics, 2022]. The increase in diesel prices led to an increase in the hydrogen delivery cost, which resulted in higher retail prices for hydrogen in 2022. There was also a major increase in retail hydrogen prices at the beginning of 2023. This was attributed to increases in feedstock costs and significant decreases in the value of LCFS credits [Iwatani, 2022]. The price of SMR hydrogen increased as cold weather increased demand for natural gas, which drove up the price of this key feedstock. The price of electrolytic hydrogen also increased as increased power demand increased the cost of electricity [Burgess and Garg, 2023]. This episode indicates that hydrogen prices are sensitive to the price of feedstocks. This also raises interesting questions about hydrogen pricing, specifically about the impact that weather and seasonality can have on hydrogen prices. It also raises questions about how "sticky" hydrogen prices are and how hydrogen prices will respond if the cost of feedstocks begins to decrease.

CALSTART analyzed the cost components for retail hydrogen in Figure 16. The cost of retail hydrogen was broken down into several components, including cost of hydrogen production, cost of distributing and transporting the hydrogen to the station, levelized cost of the hydrogen station equipment, levelized cost of constructing the hydrogen station, and operational expenditures (OPEX) associated with operating the station. While there are other factors at play, the main driver behind hydrogen's high price is that current hydrogen sales volumes are low. As sales volume increases, the price of hydrogen is expected to decrease as economies of scale are reached.[41]

Figure 16. Current Retail Hydrogen Price Breakdown



[41] The methodology for this cost breakdown can be found in **Appendix H. Retail Hydrogen Costs**.

Current Cost Reduction Activities and Cost Targets

DOE is taking action to help reduce the price of hydrogen. In 2020, DOE announced the Hydrogen Earthshot program, which aims to reduce the price of low-carbon hydrogen produced from renewable energy sources. According to DOE, electrolytic hydrogen costs about $5 per kg to produce. (This amount includes only production costs and does not include the cost of transporting, compressing, or dispensing the hydrogen.) The Hydrogen Earthshot program's goal is to reduce the cost of producing hydrogen to $2 per kg by 2026 and to $1 per kg by 2030. To achieve this, Hydrogen Earthshot will increase the technology readiness for low temperature electrolyzers (i.e., alkaline and PEM electrolyzers) and high temperature electrolyzers (i.e., solid oxide electrolyzers, or SOECs).

The main objective of Hydrogen Earthshot is to improve electrolyzer technology so that it can be commercialized and enable mass production of hydrogen. This mass production would help hydrogen achieve economies of scale and consequently lower prices. To support these goals, DOE set several technical targets for electrolyzers. These technical targets (Table 8) focus on increasing the energy efficiency of the electrolyzer to reduce the amount of energy required to produce hydrogen. The technical targets also focus on reducing the cost of the stack and CAPEX of the electrolyzer system. Hydrogen Earthshot also seeks to increase the durability and lifetime of electrolyzers.

Table 8. Hydrogen Earthshot Technical Targets for PEM and SOEC [DOE, 2021a]

Electrolyzer goals for 2025	Unit	PEM	SOEC
Higher electrical efficiency	% (LHV)	≥ 70	≥ 98
Lower stack costs	$/kW	≤ 100	≤ 100
Increased durability	hours	80,000	60,000
Lower system CAPEX	$/kW	≤ 250	≤ 300

While Hydrogen Earthshot aims to reduce the production cost of hydrogen, other factors affect at-the-pump price like transportation and fueling station costs, which must also be addressed to reduce the price of hydrogen. Hydrogen is primarily transported by truck and can be delivered in either gaseous or liquid form. This mode of transportation, however, is expensive and contributes greatly to the cost of hydrogen. Other methods for transporting hydrogen, like pipelines, could potentially reduce the cost, but pipelines are economically feasible only with large volumes of hydrogen. According to Bloomberg New Energy

Finance, pipelines become viable at volumes of more than 10 tons of hydrogen per day, so pipelines will not be economically viable until there is a much larger demand for hydrogen [BloombergNEF, 2020].

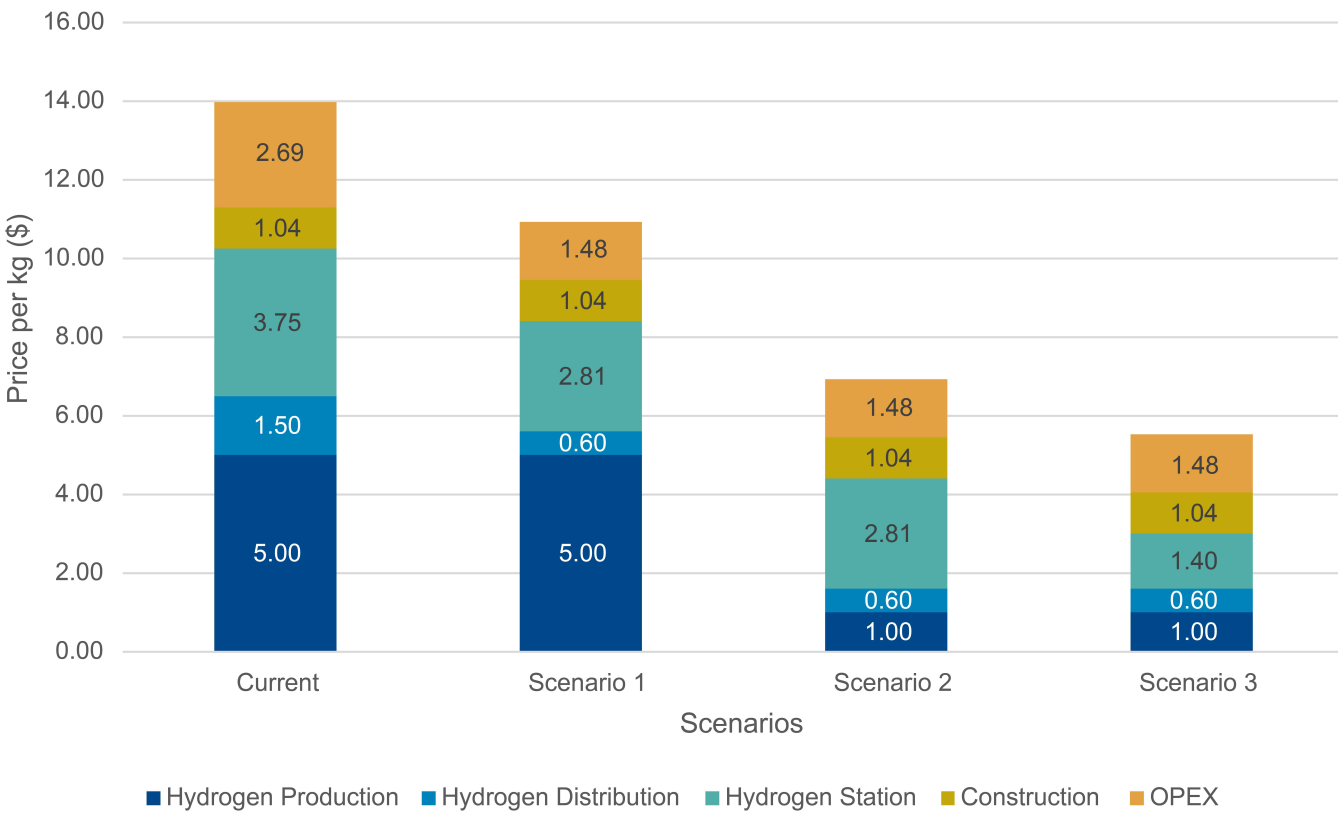
One possible solution would be to use the existing natural gas pipeline to transport hydrogen. However, several technical issues need to be resolved to effectively use those pipelines. The current pipeline network is made of steel—hydrogen causes embrittlement in steel, which threatens the integrity of the pipeline. Embrittlement can be mitigated by blending hydrogen into a natural gas pipeline. Some European countries have found that hydrogen can be injected into a natural gas pipeline at a maximum of a 10% mix. In 2021, DOE convened the HyBlend consortium to investigate the feasibility of blending hydrogen into the U.S. natural gas pipeline system [Office of Energy Efficiency & Renewable Energy, 2021].

The cost of the hydrogen station will also need to decrease. Compressors and hydrogen storage tanks are the most expensive items and constitute the majority of station costs. Advancements that decrease the cost of these components would then help to reduce the cost of the station. These components are manufactured in small quantities, so as more hydrogen stations are built, these components are expected to benefit from economies of scale. See the previous **Vehicle Costs and Component Cost Contributions** section for the complete discussion on this topic.

Projected Cost of Hydrogen

The cost of hydrogen is expected to decrease as sales volumes increase and the market for hydrogen becomes more mature. In Figure 17 below, CALSTART modeled potential pathways under which the price of different cost components for retail hydrogen can decrease.

Figure 17. Cost Components for Retail Hydrogen



Scenario 1 outlines the projected cost of hydrogen due to maturity of the market. Under this scenario, the cost of hydrogen distribution and OPEX of the station decreases (based on market projections from Shell) [Munster, 2018]. The cost of the hydrogen station also decreases as hydrogen station components are produced at higher volumes. Under Scenario 1, the price of hydrogen will decrease to $10.93 per kg.

Scenario 2 combines Scenario 1 with decreases in hydrogen production cost. Under this scenario, the DOE Hydrogen Earthshot objective of hydrogen production costs of $1 per kg is achieved. Under Scenario 2, the price of hydrogen decreases to $6.93 per kg.

Scenario 3 combines Scenario 2 with incentives for hydrogen station equipment. Under this scenario, the station owner receives an incentive equal to half the cost of the hydrogen station equipment, effectively decreasing the cost of hydrogen stations by 50%. This 50%

incentive corresponds with the incentives provided by the EnergIIZE program. Under Scenario 3, the price of hydrogen decreases to $5.52 per kg.

These developments would cause a significant decrease in the price of hydrogen. Price decreases of this magnitude would be consistent with the FCET market reaching Phase 3 (Growth).[42]

Inflation Reduction Act

As mentioned previously in the **FCET Commercialization Roadmap**, the Inflation Reduction Act is a landmark climate bill. Certain provisions will not only help drive down the cost of these vehicles but also the price of hydrogen.

Section 13204 – Alternative Fuel Vehicle Refueling Property Credit

This legislation creates a tax credit equal to 30% of the cost of any qualified alternative fuel vehicle refueling property placed in service and 20% for allowable expenses in excess of the $100,000 limitation. This tax credit for hydrogen fueling stations will extend to December 31, 2031.

Section 13404 – Hydrogen Production Tax Credit

This legislation offers tax credit for hydrogen production for 10 years after a clean hydrogen production facility starts operating. The hydrogen must be produced in the United States to qualify, and construction of the hydrogen facility must begin after December 31, 2021, and before December 31, 2028. Section 136204 offers tax credit per kg of hydrogen based on a base rate of $0.60 per kg multiplied by applicable rate in Table 9. If the hydrogen is produced at a facility that meets prevailing wage and registered apprenticeship program requirements, the amount of the tax credit is increased by a factor of five, for a maximum of $3 per kg.

[42] The methodology for this analysis can be found in **Appendix H. Retail Hydrogen Costs**.

Table 9. Hydrogen Production Tax Credit Formula[43]

Kg of CO2e per kg of Hydrogen	Applicable Rate	Maximum Tax Credit per kg of Hydrogen	Production Pathway
4	20%	$0.60	Biomass to GH2 GH2 from SMR with Sequestration* GH2 from RNG
2.5	25%	$0.75	GH2 from nuclear GH2 from solar or wind GH2 from High temperature electrolysis
1.5	33.4%	$1.00	No production pathways examined fall into this category
0.45	100%	$3.00	LH2 from SMR of RNG with Sequestration* GH2 from SMR of RNG with Sequestration*

Action Items

CALSTART's projections shown above indicate that with economies of scale, a decrease in the cost of hydrogen production, and incentive funding for hydrogen stations, the price of hydrogen can fall to $5.52 per kg. This price is still higher than the diesel price of $4 per kg, so further action will need to be taken to reach price parity with diesel. Cost parity with diesel can be achieved by including hydrogen in environmental credit programs.

A. Modify Renewable Fuel Standard Program/Renewable Identification Number Credits to Include Hydrogen

Renewable Fuel Standard Program (RFSP) is a federal program managed by the U.S. Environmental Protection Agency (EPA) that originated with the Energy Policy Act of 2005 and was expanded with the Energy Independence and Security Act of 2007 [EPA, 2022]. For fleets to gain credits, renewable fuel must be blended into transportation fuel in

[43] The carbon intensity of the hydrogen pathways was calculated using the Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) Model. An asterisk indicates data was pulled using the 2020 GREET Model. No asterisk means the 2021 GREET Model was used. These figures are based on data from GREET. These figures represent averages for each production pathway. The actual emissions from individual production projects can differ from these values. SMR baseline was calculated to be 11.65 kg of CO2e per kg of hydrogen.

increasing amounts each year. These renewable fuels are tracked by renewable identification number (RIN) credits. One RIN is equivalent to one gallon of ethanol, and one gallon of biodiesel is equivalent to 1.5 RINs [EPA, 2022a]. RINs are generated when a renewable fuel is produced; RINs are held by the entity that generates or imports the renewable fuel. If the renewable fuel is sold, the RINs can be sold with the fuel. If a fuel provider purchases renewable fuel to blend into a transportation fuel, they can retire the attached RINs to comply with RFSP.

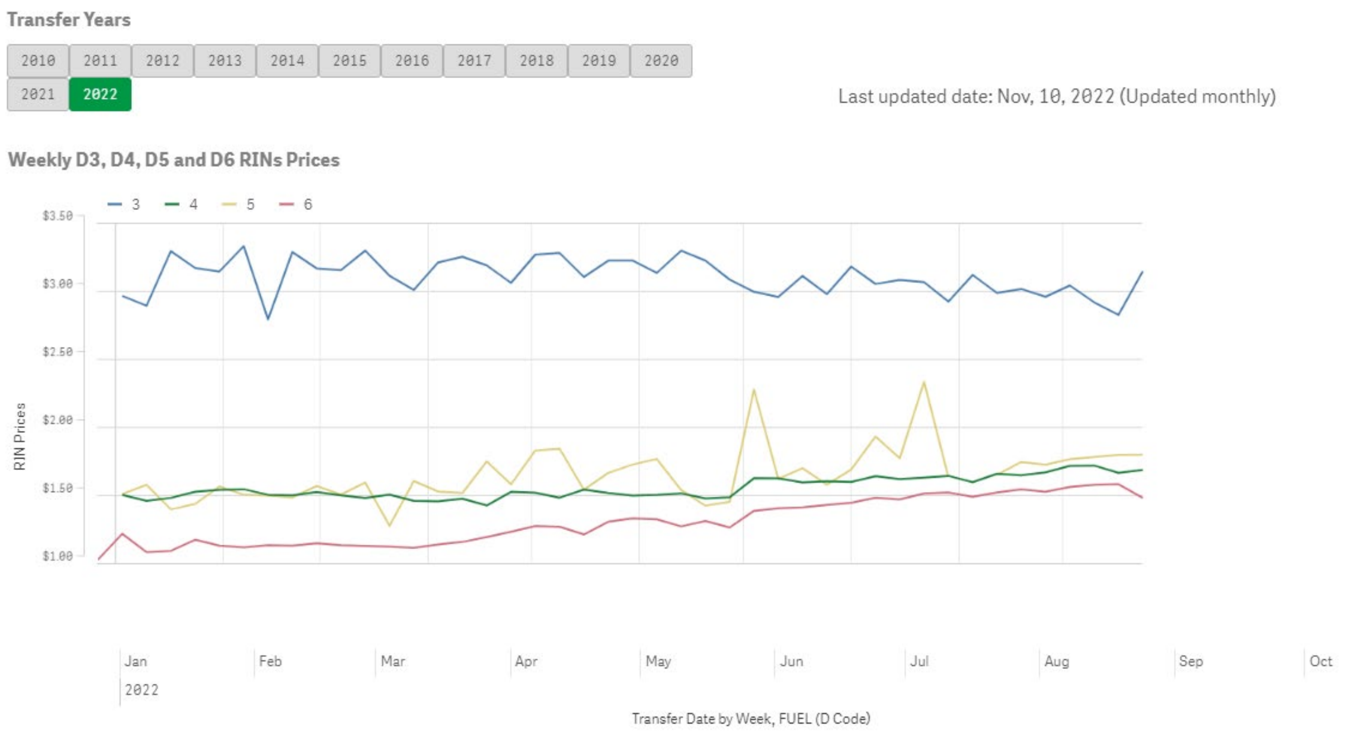
Once a fuel producer has met its obligations under RFSP (i.e., reaching the minimum percentage of renewable fuels that must be blended into transportation fuel), excess RINs can be separated from the renewable fuel and sold. RINs are usually sold on EPA's Moderated Transaction System to fuel providers that have not blended enough renewable fuel into transportation fuel. Eligible fuels and respective price floors and ceilings have been set as detailed in Table 10 and Figure 18.

Table 10. RIN Eligible Fuels and Price Range

RIN Class	Eligible Fuels	Minimum Price	Maximum Price
D3	Cellulosic biofuel produced from cellulose, hemicellulose, or lignin; must reduce life-cycle GHG emissions by at least 60% from petroleum. Includes renewable CNG, renewable liquefied natural gas, and renewable electricity from biogas from landfills, municipal wastewater treatment facility digesters, agricultural digesters, and separated municipal solid waste digesters; and biogas from the cellulosic components of biomass processed in other waste digesters.	\$0.05	\$3.50
D4	Biomass-based diesel made from biodiesel and renewable diesel; must reduce life-cycle GHG emissions by at least 50% from petroleum.	\$0.05	\$3.00
D5	Advanced biofuels made from renewable biomass except corn starch ethanol; must reduce life-cycle GHG emissions by at least 50% from petroleum. Includes renewable CNG, renewable liquefied natural gas, and renewable electricity from biogas from waste digesters.	\$0.05	\$3.00

RIN Class	Eligible Fuels	Minimum Price	Maximum Price
D6	Renewable fuel made from ethanol from corn starch or any other qualifying renewable fuel.	$0.05	$3.00

Figure 18. RINs Market Prices in 2022 [EPA, 2022b]



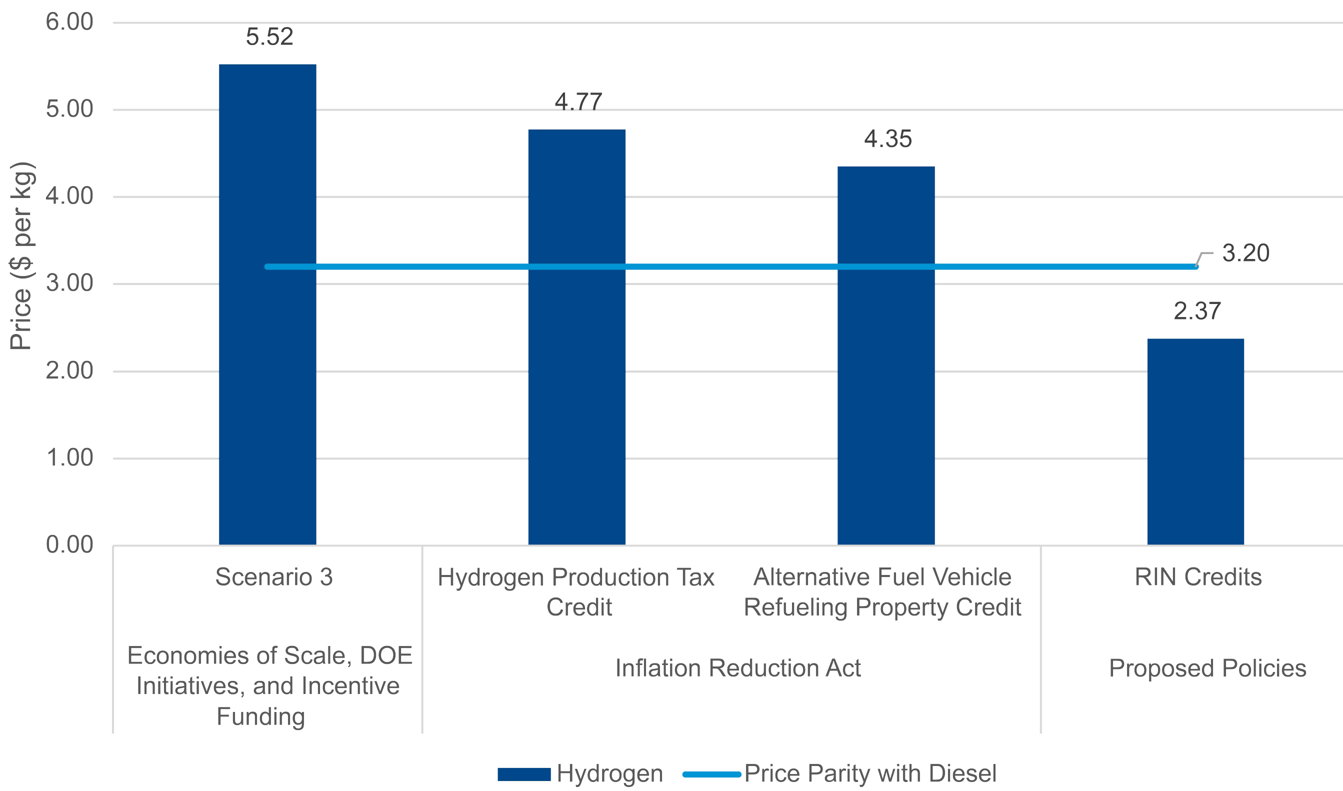
As shown above, hydrogen is not eligible to earn RIN credits even if it is produced from renewable sources [Burke, 2018]. Making an RIN pathway for hydrogen could help to reduce the price and attain cost parity with other fuels. For example, renewable CNG is eligible for D-5 RINs; between January–October 2022, D-5 traded at an average price of $1.63. If renewable hydrogen was included in D-5 RINs on a diesel-gallon equivalent basis, the RINs should equal about $2.45 per kg of hydrogen. Hydrogen could also be made eligible under D-6. Between January–October 2022, D-6 RINs traded at an average price of $1.32. If renewable hydrogen was included in D-6 RINs on a diesel gallon equivalent basis, the RINs should equal about $1.98 per kg.

To create a new hydrogen pathway, a fuel type, feedstock, and production process must be specified and approved. Air Liquide has submitted a request to obtain gaseous and liquid hydrogen produced from renewable biogas via SMR approved as a pathway, and FuelCell Energy has also submitted an application to obtain gaseous hydrogen from renewable biogas feedstock via SMR approved [EPA, 2022c]. The current RIN definition allows for fuels only derived from biomass. While hydrogen produced from biogas can potentially be considered a renewable fuel, this definition effectively excludes electrolytic hydrogen from being awarded RINs credits. As such, CALSTART recommends modifying the Energy Policy Act of 2005 to change the definition of renewable fuel so that electrolytic hydrogen and other forms of low-carbon hydrogen could be eligible to receive RIN credits.

Impact on the Price of Hydrogen

To reach Phase 4 (Maturity) of commercialization, hydrogen will need to reach price parity with diesel. In Figure 19, CALSTART analyzed the impacts that the proposed policies described above—the Hydrogen Production Tax Credit, the Alternative Fuel Vehicle Refueling Property Credit, and the recommended RIN pathway for hydrogen—will have on the retail price of hydrogen.[44]

Figure 19. Projected Impact of Proposed Policies on the Retail Price of Hydrogen



This analysis assumed that the entirety of the benefits of these policies are passed on to the customer at the pump. Under Scenario 3 (as described in Figure 17), the price of hydrogen will be $5.52. The provisions passed under the Inflation Reduction Act will be able to drive the price down to $4.35 per kg, which is still above the diesel parity price of $3.20 per kg [Munster, 2018]. However, creating an RIN credits pathway for low-carbon hydrogen has

[44] The methodology for this analysis is found in **Appendix H. Retail Hydrogen Costs**.

the potential to decrease the price to $2.37 per kg, which would allow hydrogen to be cost competitive with diesel.

Conclusion

A general perception exists that FCET commercialization lags far behind BET commercialization. Advancements in FCET technology made over the last few years are the result of industry research, development efforts, and government funding for demonstration projects. While Class 8 FCETs are emerging as a commercialized product, few trucks have been deployed, meaning these technological developments do not equate to commercial readiness. Based on the commercialization stages outlined in this report, the FCET market is currently transitioning from Phase 1 (Introduction) to Phase 2 (Development). The start of the NorCAL Zero-Emission Regional Drayage Project in 2023 will mark the beginning of Phase 2.

Several actions must be taken to advance the commercialization of FCETs in California beyond Phase 2. Fleets have stated that TCO poses a serious barrier to adoption, citing the higher upfront capital costs specifically. Government action will be necessary to help offset these costs. These concerns can be addressed by funding vehicle deployments to encourage economies of scale and enacting a series of tax incentives for FCETs.

Fleets also need reassurance that FCET adoption will not disrupt their current operations. Fleets in general have little operational experience with FCETs and have expressed concerns about operational aspects such as the availability of a maintenance workforce, the fueling speed of the vehicles, and reduced ability to carry cargo due to the weight penalty. CALSTART recommends facilitating a loaner program so fleets can gain operational experience with FCETs, as well as funding to implement technological solutions that will increase the fueling speed and address the weight penalty. Furthermore, the State of California should invest in workforce development initiatives, especially given that the zero-emission industry currently lacks both engineers and technicians.

Ensuring the availability of hydrogen and refueling infrastructure is absolutely necessary for FCET commercialization. This issue must be met on two fronts. First, hydrogen production capacity must increase rapidly to meet projected demand for Class 8 FCETs, even in a low-uptake scenario. CALSTART estimates that, assuming the minimum requirements of the proposed ACF regulation, demand for hydrogen in California will quickly outpace supply, which will serve as a major constraint on the market. If there is more aggressive adoption of Class 8 FCETs, this supply issue will become an even greater constraint. Government funding can help to support hydrogen production.

Second, the development of a hydrogen fueling network is critical to address the causality dilemma the FCET market currently faces. Fortunately, progress has been made toward addressing this problem. With the assistance of state funding, HD hydrogen fueling stations are being deployed in first-mover clusters. The beginnings of hydrogen fueling corridors are also starting to emerge. CALSTART has identified the deployment of 500–900 FCETs as an early sign that the market has advanced to Phase 3 (Growth). Although CALSTART does not expect this number of deployments in the near future, this study projects that there will be enough fueling capacity in California by 2024 to serve 500–900 FCETs. Building out the hydrogen fueling network ahead of FCET sales will help to facilitate early deployments. However, despite this progress, the hydrogen fueling network will need additional development to support a rapidly growing market for FCETs. Government funding can help to support the continued build out of a hydrogen fueling network. Moreover, the cost of retail hydrogen must decrease for this fuel to be financially viable for fleets—a series of tax incentives for hydrogen production and the development of an RINs pathway for low-carbon hydrogen production can drive the retail cost down significantly.

These actions will enable the uptake of FCETs, which is required to advance commercialization to Phase 3 (Growth) and Phase 4 (Maturity). To close these gaps, industry must prepare markets for hydrogen fuel cell technology. Implementing the recommendations in this report with help create the pathways to ensure adequate hydrogen production capacity, deploy hydrogen infrastructure, and reduce the price of hydrogen. The market's chicken and egg problem will persist until hydrogen production and fueling infrastructure is in place to facilitate on-road deployments. Even then, further action will need to be taken to lower the price of FCETs, advance technological development and user acceptance, and address other factors that act as barriers to adoption.

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Appendix A. Class 8 FCET Market Opportunity Research Methodology

CALSTART estimated the potential size of the Class 8 FCET market in California through 2045. This analysis assumed that ZET adoption will be driven by California's regulatory environment since ZETs currently have a higher capital cost than traditional internal combustion engine vehicles. As a result, it was assumed that fleets would not adopt ZETs in the absence of a mandate.

California has regulations to encourage the adoption of zero-emission transportation technology. The ACT rule establishes minimum sales requirements for ZETs. The ACT rule applies to sales of Class 2b–8 trucks in California. Under the ACT rule, truck OEMs are required to have an increasing percentage of their California truck sales be zero-emission. The regulation takes effect in 2024, at which point 5% of Class 2b–3 truck sales, 9% of Class 4–8 straight truck sales, and 5% of truck tractor sales must be zero-emission. The sales requirement increases incrementally over time until 2035 when 55% of Class 2b–3 truck sales, 75% of Class 4–8 straight truck sales, and 40% of truck tractor sales must be zero-emission.

California has also proposed the ACF regulation. While the ACT rule requires OEMs to sell ZETs, the proposed ACF regulation will require certain fleets to purchase them. The draft regulation applies to fleets owned by state, local, and federal government agencies. In addition, High Priority fleets, or private fleets that have 50 or more trucks or generate $50 million or more in annual revenue, are also subject to the ACF regulation.

CALSTART assumed that the ACF regulation will be the main driver of ZET adoption. The regulation applies directly to fleets, which impacts their purchasing decisions. This analysis began by estimating the number of Class 8 trucks that are subject to the ACF regulation. When the ACT rule was enacted, it included a Large Entity Reporting requirement for fleets that operated a facility in California in 2019 and meet any of the following criteria to report the number of trucks they operate or control to CARB:

- Had gross annual revenues greater than $50 million in the United States for the 2019 tax year, including revenues from all subsidiaries, subdivisions, or branches, and had one or more vehicles over 8,500 pounds GVWR under common ownership or control that were operated in California in 2019; or
- Any fleet owner in the 2019 calendar year that had 50 or more vehicles over 8,500 pounds GVWR under common ownership or control; or

- Any broker or entity that dispatched 50 or more vehicles over 8,500 pounds GVWR into or throughout California in the 2019 calendar year; or
- Any California government agency including all state and local municipalities that had one or more vehicles over 8,500 pounds GVWR that were operated in California in 2019; or
- Any federal government agency that had one or more vehicles over 8,500 pounds GVWR that were operated in California in 2019.

CARB published the data gathered from Large Entity Reporting.[45] This data was broken down by truck vocation and geographically (by Air Basin). CALSTART aggregated this data to understand the number of trucks that are subject to this regulation. CALSTART included Class 8 day cab and sleeper cab trucks in this count.

This analysis assumed that the Class 8 truck market will grow over time. CALSTART estimated this growth by using data from FAF4 [Bureau of Transportation Statistics, 2021].[46] This data uses ton-miles as a metric for the amount of freight. This data is broken up by California region[47] and whether freight transported was domestic, an import, or an export. It also forecasts baseline, pessimistic, and optimistic ton-miles transported between 2020–2045; baseline estimates were used to approximate change from current ton-miles transported. The number of Class 8 trucks was assumed to increase proportionately with increases in forecasted ton-miles. This assumption was used to calculate the number of Class 8 trucks subject to the ACF regulation for each year between 2022 and 2045.

CALSTART then calculated the adoption of ZETs. The proposed ACF regulation applies to a wide range of MHD truck vocations that have a GVWR of greater than 8,500 pounds. Under the current draft ACF regulation,[48] there are multiple ways that fleets can comply. High Priority fleets can comply with ACF in one of two ways. The first method is through the Model Year Schedule. Under this method, High Priority fleets must only purchase zero-emission MHD vehicles starting in 2024 and must also remove internal combustion engine vehicles when they reach the end of their useful life. The Model Year Schedule effectively requires High

[45] The Large Entity Reporting data can be found at https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks/large-entity-reporting.

[46] FAF4 provides a comprehensive picture of ton-miles of goods transported by truck in California. A ton-mile equals 1 ton traveling 1 mile.

[47] FAF4 data by region includes the Los Angeles/Long Beach region, Sacramento-Roseville region, San Diego-Carlsbad-San Marcos region, San Jose-San Francisco-Oakland region, Fresno-Madera region, and the rest of California.

[48] Proposed draft regulation dated October 27, 2022. Information about the draft regulation can be found at https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-fleets-regulation-summary.

Priority fleets to replace their existing vehicles with zero-emission technology once they reach the end of their useful life. Alternatively, High Priority fleets can comply using the ZEV Milestone Schedule. This compliance pathway allows fleets to meet ZEV targets, expressed as a percentage of their total fleet. The ZEV Milestone Schedule provides targets that must be reached for each type of vehicle. At the time of writing, the proposed targets are displayed in Table A-1. Based on the proposed targets, fleets would not be required to adopt day cab tractors until 2027 and sleeper cab tractors until 2030.

Table A-1. ZEV Milestone Schedule [CARB, 2022d]

Percentage of vehicles that must be zero-emission	10%	25%	50%	75%	100%
Milestone Group 1: Box trucks, vans, buses with two axles, yard tractors, light-duty package delivery vehicles	2025	2028	2031	2033	2035 and beyond
Milestone Group 2: Work trucks, day cab tractors, buses with three axles	2027	2030	2033	2036	2039 and beyond
Milestone Group 3: Sleeper cab tractors and specialty vehicles	2030	2033	2036	2039	2042 and beyond

CALSTART used the ZEV Milestone Schedule to calculate the number of ZETs that will be deployed. Since it was assumed that ZET adoption will be driven by the regulatory environment, this calculation assumed that the market would achieve minimum compliance with the ACF regulation.[49] CALSTART multiplied the number of day cab tractors and sleeper cab tractors in each year between 2022 and 2045 by the target percentage to calculate ZETs deployed in each year, which calculated the addressable market for ZETs.

The potential Class 8 FCET sales within the larger ZET market were estimated using specific use cases for both BETs and FCETs. CALSTART assumed that there were some use cases where BETs would dominate the market, others where FCETs would dominate, and still additional cases where the two technologies would compete. CALSTART assumed that fleets will aim to use the cheapest technology that can achieve a 1-to-1 replacement with diesel trucks.

[49] Since CARB funding cannot be used for ACF compliance, this could incentivize fleets to make early FCET purchases. Early purchases would allow fleets to take advantage of CARB-funded vehicle incentive programs before they are required to comply with ACF and lose access to this funding. As a result, this could induce fleets to adopt FCETs ahead of their compliance schedule.

BETs were assumed to be the dominant technology for duty cycles of 100 or fewer miles per day. FCETs were assumed to be the dominant technology for duty cycles of 300 or more miles per day. All other duty cycles were considered to be contested for which BETs and FCETs will compete for market share. Large Entity Reporting data was aggregated by duty cycle and provided the number of trucks that fall into each category.

Appendix B. Emissions Analysis

The emissions analysis in this report investigated GHG emissions as well as criteria pollutants, including NOx, CO, PM10, and PM2.5. Emissions produced by trucks can be divided into two types. Upstream emissions occur during the production and distribution of the fuel consumed by the truck. Most Class 8 trucks consume diesel, and the upstream emissions will consist of the emissions generated in the production of diesel. For FCETs, the upstream emissions will consist of emissions that are produced during the production and distribution of hydrogen. There are also tailpipe emissions, which are produced directly by the truck when it is being operated. Life-cycle emissions consist of the sum of upstream and tailpipe emissions.

Upstream emissions were calculated using Argonne National Lab's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) 2021 Model. The GREET Model calculates upstream emissions per unit of fuel energy content for each individual hydrogen production pathway. The GREET Model expresses the upstream emissions as grams of CO2 equivalent per million British Thermal Units (MMBtu). These units were converted to kg of CO2 equivalent per kg of hydrogen produced. An example of this conversion is included below for a compressed hydrogen (produced via SMR) pathway:

$$\frac{102{,}427 g\ CO2e}{mmBTU\ H2} * \left(\frac{1\ kg\ CO2e}{1{,}000\ g\ CO2e}\right) * \left(\frac{1\ mmBTU\ H2^{50}}{1055.1\ MJ\ H2}\right) * \left(\frac{120\ MJ\ H2^{51}}{1\ kg\ H2}\right) = \frac{11.65\ kg\ CO2e}{kg\ H2}$$

It is important to note that fuel cell drivetrains are more efficient than internal combustion engines. As a result, the upstream emissions calculations were adjusted to account for this efficiency. The fuel cell was assumed to be 30% more efficient than an internal combustion engine. Fuel cell drivetrains are expected to become more efficient over time, meaning upstream emissions for FCETs are subject to decrease in the future. California's SB 1505 requires that 33.3% of hydrogen dispensed at hydrogen fueling stations that are funded by the state come from renewable sources. However, the LCFS HRI program and many CEC-funded hydrogen stations have a 40% renewable content requirement [CARB, 2022c]. As a result, this analysis assumed that 40% of hydrogen is renewable hydrogen and adjusted the carbon intensity accordingly.

[50] Conversion factor provided by the Canada Energy Regulator at https://apps.cer-rec.gc.ca/Conversion/conversion-tables.aspx#1-7.

[51] Conversion factor provided by DOE at https://www.energy.gov/eere/fuelcells/hydrogen-storage.

Tailpipe emissions were calculated using CARB's 2021 Emission Factor Calculator (EMFAC) model. This model provides estimates of on-road emission rates (expressed in grams per mile) for the operation of the vehicle. The model also provides information on other truck functions that release emissions, like idling and starting up the vehicle. Idling emissions were expressed as grams per day and were added to emissions produced by operating the truck. Start-up emissions were expressed as grams of emissions per vehicle start up. This analysis assumed that the trucks went on two trips per day and therefore started up twice per day. The assumptions programmed into EMFAC were as follows:

- Region: Statewide (all of California)
- Season: Annual
- Model Year: 2024
- Speed: Aggregate

EMFAC was used to compare emissions between Class 8 diesel trucks and FCETs. EMFAC does not have data for FCETs, so CALSTART used EMFAC data for BETs and assumed that FCETs will produce the same number of emissions. Emissions comparisons were calculated for several types of trucks and duty cycles. Emissions calculations were provided for trucks servicing ports, including the Ports of Los Angeles and Long Beach, the Port of Oakland, and all other California ports (Other Ports). In addition, emissions calculations were provided for Class 8 trucks that do not serve ports (Non-port Class 8 Trucks).

It is important to note that FCETs do not produce tailpipe emissions for GHGs, CO, or NOx. As a result, these pollutants will come from upstream emissions only.

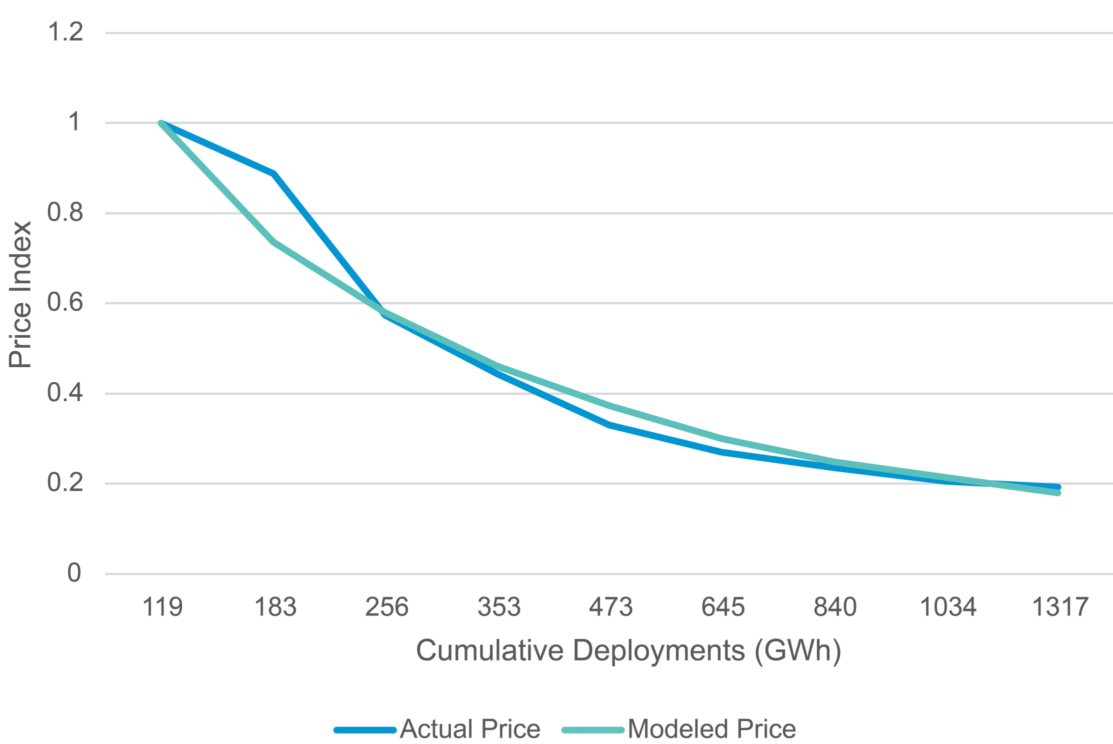
Appendix C. Class 8 FCET Costs

Learning Rates Methodology

CALSTART analyzed the impact that economies of scale would have on the FCET and hydrogen industry and the effect on the price of both FCETs and hydrogen. The impact of economies of scale was modelled using a methodology borrowed from a study conducted by Elenora Ruffini and Max Wei [Ruffini, 2018]. This study used learning rates to model how price changes in response to increases in production volume. A learning rate is expressed as a percentage. It represents the percent decrease in the price of a good that occurs when production volume doubles. CALSTART used this methodology to project price based on different production volumes.

This methodology has proven to be highly reliable for estimating the impacts of economies of scale for other technologies. CALSTART tested this methodology on the lithium-ion battery pack market to confirm its validity. This test used battery pack pricing data from Bloomberg NEF and a learning rate of 39% from Hydrogen Council [BloombergNEF, 2021; Hydrogen Council, 2020]. The actual results are very close to the modelled results (Figure C-1).

Figure C-1. Comparison of Actual Data vs. Learning Rates Approach



Economies of Scale

CALSTART used the learning rates methodology to estimate the impact that economies of scale will have on major components. For this analysis, it was assumed that the PEMFC and onboard hydrogen storage tanks have the greatest potential to benefit from economies of scale. CALSTART conducted this analysis for PEMFCs and onboard hydrogen storage tanks. To calculate future pricing, CALSTART used the learning rates methodology to project the impact that economies of scale will have on the price of each component/system. The learning rates for PEMFCs and onboard hydrogen storage tanks are provided in Table C-1 below.

Table C-1. Learning Rates for PEMFCs and Onboard Hydrogen Storage Tanks

FCET Vehicle Component	Learning Rate	Source
PEMFC	11%	Hydrogen Council, 2020
Onboard Hydrogen Storage Tanks	10%	Ruffini, 2018

Class 8 FCET Costs

CALSTART conducted an analysis of Class 8 FCET costs, starting with pricing for two types of vehicles: a demonstration FCET and a commercial FCET. A demonstration FCET is defined as an FCET that is in the earlier stages of commercialization; is intended to be deployed in a pilot demonstration with a fleet; and is produced in low volumes. Demonstrations allow OEMs to further develop their vehicle and transition into producing commercial FCETs. Commercial FCETs are a commercialized product that is ready for the market. Commercial FCETs are cheaper than demonstration vehicles because OEMs typically have standardized components and an established manufacturing process. CALSTART found that a typical demonstration Class 8 FCET costs about $1 million. A commercial Class 8 FCET currently costs about $700,000.[52]

CALSTART also analyzed the future price of Class 8 FCETs. CALSTART assumed that the cost of FCETs and major component systems would decrease over time as the industry benefits

[52] Based on prices of BETs and FCETs that were funded under CEC's GFO-20-606 solicitation. CALSTART obtained BET and FCET pricing data from this solicitation from a public records request. The prices of BETs and FCETs were calculated by taking the average price of BETs and FCETs funded under this solicitation. For more information about GFO-20-606, visit https://www.energy.ca.gov/solicitations/2020-11/gfo-20-606-zero-emission-drayage-truck-and-infrastructure-pilot-project.

from economies of scale. To conduct this analysis, CALSTART determined the cost of current vehicles and broke down the cost by components/systems. CALSTART provided a cost breakdown of a demonstration FCET and a commercial FCET by component/system. CALSTART then projected the future price of each component/system to understand how economies of scale will impact the price of the FCET. This analysis was conducted based on the low-uptake projection (133,458 Class 8 FCETs deployed by 2045) and the high-uptake projection (167,255 Class 8 FCETs deployed by 2045) that were developed in the **FCET Market Opportunity** section. The assumptions for these projections are displayed in Table C-2 through Table C-5 below.

Table C-2. Demonstration Class 8 FCET Cost Assumptions

FCET Vehicle Component	Size	Cost per Unit	Source
PEMFC Stack	200 kW	$920/kW	Learning Rates Methodology
Battery	150 kWh	$1,000/kWh	YUNEV LLC (2021)
Hydrogen Storage Tank	50 kg	$1,200/kg	Learning Rates Methodology
Motor and Power Electronics	500 kW	$49.2/kW	Hunter et al. (2021)
Cab and Chassis	-	$165,000	-
Other	-	-	-

Table C-3. Commercial Class 8 FCET Cost Assumptions

FCET Vehicle Component	Size	Cost per Unit	Source
PEMFC Stack	200 kW	$752/kW	Learning Rates Methodology
Battery	150 kWh	$500/kWh	YUNEV LLC (2021)
Hydrogen Storage Tank	50 kg	$1,080/kg	Learning Rates Methodology
Motor and Power Electronics	500 kW	$49.2/kW	Hunter et al. (2021)
Cab and Chassis	-	$165,000	-
Other	-	-	-

Table C-4. Class 8 FCET Cost Assumptions: Low-Uptake Projection

FCET Vehicle Component	Size	Cost per Unit	Source
PEMFC Stack	200 kW	$119/kW	Learning Rates Methodology
Battery	150 kWh	$300/kWh	YUNEV LLC (2021)
Hydrogen Storage Tank	50 kg	$500/kg	Learning Rates Methodology
Motor and Power Electronics	500 kW	$41.7/kW	Hunter et al. (2021)
Cab and Chassis	-	$150,000[53]	-
Other	-	-	-

Table C-5. Class 8 FCET Cost Assumptions: High-Uptake Projection

FCET Vehicle Component	Size	Cost per Unit	Source
PEMFC Stack	200 kW	$96/kW	Learning Rates Methodology
Battery	150 kWh	$300/kWh	YUNEV LLC (2021)
Hydrogen Storage Tank	50 kg	$411/kg	Learning Rates Methodology
Motor and Power Electronics	500 kW	$20.9/kW	Hunter et al. (2021)
Cab and Chassis	-	$150,000[54]	-
Other	-	-	-

[53] CARB assumes that integrating auxiliary electrical equipment will increase the cost of the chassis and cab by 10%. This additional cost is expected to decrease as economies of scale are achieved.

[54] CARB assumes that integrating auxiliary electrical equipment will increase the cost of the chassis and cab by 10%. This additional cost is expected to decrease as economies of scale are achieved. Learn more at https://ww2.arb.ca.gov/sites/default/files/2020-12/201207costdisc_ADA.pdf.

Impact of Inflation Reduction Act and Incentives

The Inflation Reduction Act included a provision that will help to lower the capital costs of an FCET. This legislation includes the Qualified Commercial Clean Vehicles credit. The tax credit is equal to the lesser of 30% of the cost of the qualified commercial clean vehicle or the incremental cost. The value of the credit is capped at $40,000 for vehicles weighing more than 14,000 pounds. Given the high upfront costs of an FCET, this effectively creates a $40,000 tax credit for FCETs. CALSTART assumed that this tax credit will be exercised in the year that the FCET is purchased. The impact of this policy was calculated by subtracting $40,000 from the purchase price of the FCET.

CALSTART also calculated the impact that $250,000 of funding per vehicle would have on the cost of FCETs. CALSTART calculated this impact by subtracting $250,000 from the purchase price of the FCET.

Appendix D. Hydrogen Production

California's Hydrogen Production Capacity

The hydrogen production capacity available for California's transportation market is estimated to be about 119,000 kg per day in 2024. This amount was calculated by combining information from numerous stakeholder interviews with University of California Irvine's Renewable Hydrogen Production Roadmap for California Report [Reed, 2020]. According to the report, about 55,000 kg per day of hydrogen were available to California's transportation market in 2020 (Table D-1).

Table D-1. Producers and Amount of Hydrogen Production for Transportation as of 2020

Producer	Amount of Hydrogen (kg)
Air Liquide	30,000
Stratos Fuels	5,000
Fuel Cell Energy / Toyota	1,200
H2B2	1,000
Sunline Transit	900
Air Products	Capacity unclear
Plug Power	30,000

CALSTART supplemented these values with numerous stakeholder interviews and data from public records funded by GFO-20-609 to discover hydrogen production capacity not captured in the University of California Irvine's report (Table D-2).

Table D-2. Expected Future Hydrogen Production and Capacity for Transportation

Producer	Hydrogen Production per Day (kg)
Iwatani / SG	11,000
Air Products	10,000
Raven SR / Republic Services	5,500
Stratos Fuels	5,000
Linde	1,700
Shell / Equilon	1,000

Table D-1 and Table D-2 consider hydrogen produced in California or in neighboring states. Hydrogen that must be trucked over longer distances can be expensive and is not considered to be cost competitive.

Private Investment

CALSTART calculated the amount of private investment that is required to develop hydrogen production capacity. This calculation entailed analyzing the costs associated with building hydrogen production capacity. GFO-20-609 provided funding to build hydrogen production facilities. Based on the costs identified in the proposals submitted to GFO-20-609, CALSTART calculated that the average cost per kg of daily hydrogen production capacity is approximately $6,419. CALSTART calculated the difference between projected daily hydrogen demand and current daily hydrogen production capacity to understand how much additional hydrogen production capacity is required to meet projected hydrogen demand. This figure was then multiplied by $6,419 to obtain the private investment needed to build out the required hydrogen production capacity. Based on this calculation, $40.5 billion of investment is required to meet the hydrogen demands of the low-uptake scenario, and $51 billion of investment is required to meet the hydrogen demands of the high-uptake scenario.

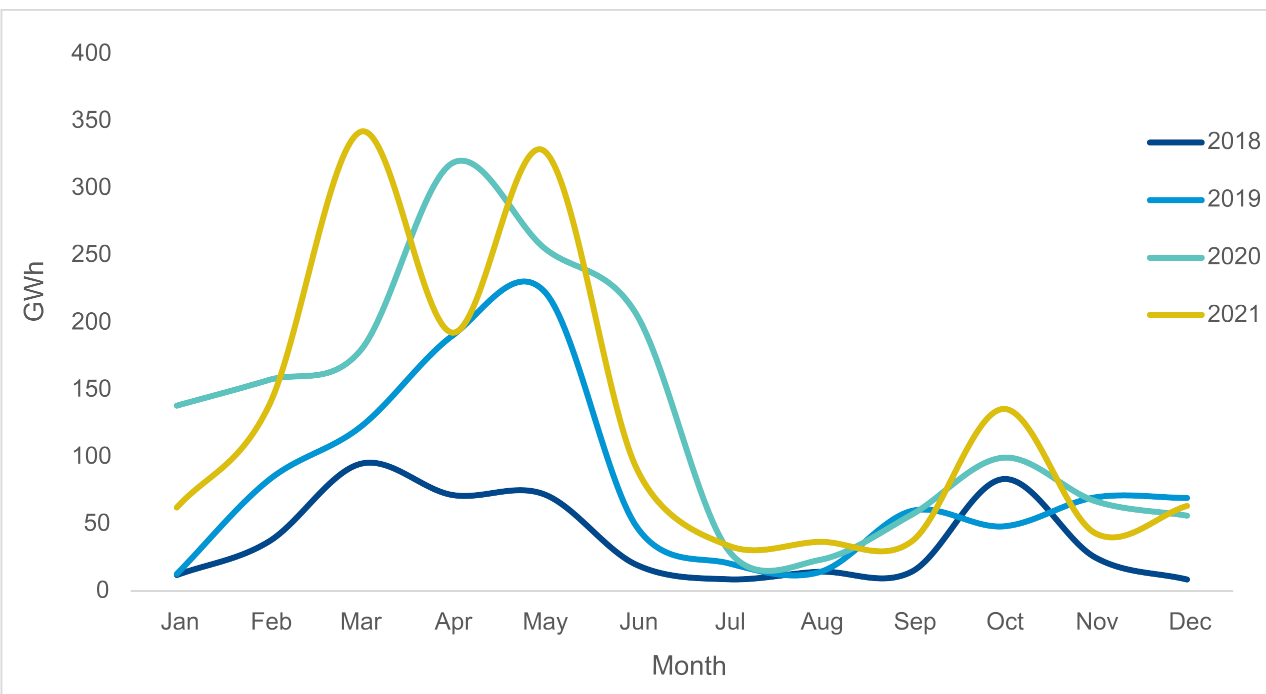
It is important to note that this analysis is based on the current cost of deploying hydrogen production capacity. This analysis does not assume that hydrogen production facilities benefit from economies of scale or experience inflation.

Appendix E. Hydrogen Production Potential with Curtailed Power

Low-carbon hydrogen generation through electrolysis may also help reduce solar and wind curtailments. For this analysis, all curtailment data was collected from CAISO [CAISO, n.d.]. The solar and wind curtailed power for 2018 to 2021 is shown in Figure E-1 below.

Power generation by renewable sectors is not uniform throughout different seasons; variability in the power generation and curtailments therefore change throughout the year. For example, curtailed power is highest during spring due to increased sunlight, leading to more energy production from solar panels. However, since temperatures are mild in spring, there is less need for air conditioning, which reduces the energy demand of home and commercial buildings. These curtailments are higher than in summer months. During the summer months, the available solar irradiation remains the same for most locations, but the demand and consumption of buildings increase due to load increases. Air conditioning requires much more energy in the summer, resulting in less power curtailment. Figure E-1 below shows the solar and wind power curtailment for the last four years in California.

Figure E-1. Current Solar and Wind Curtailment in California

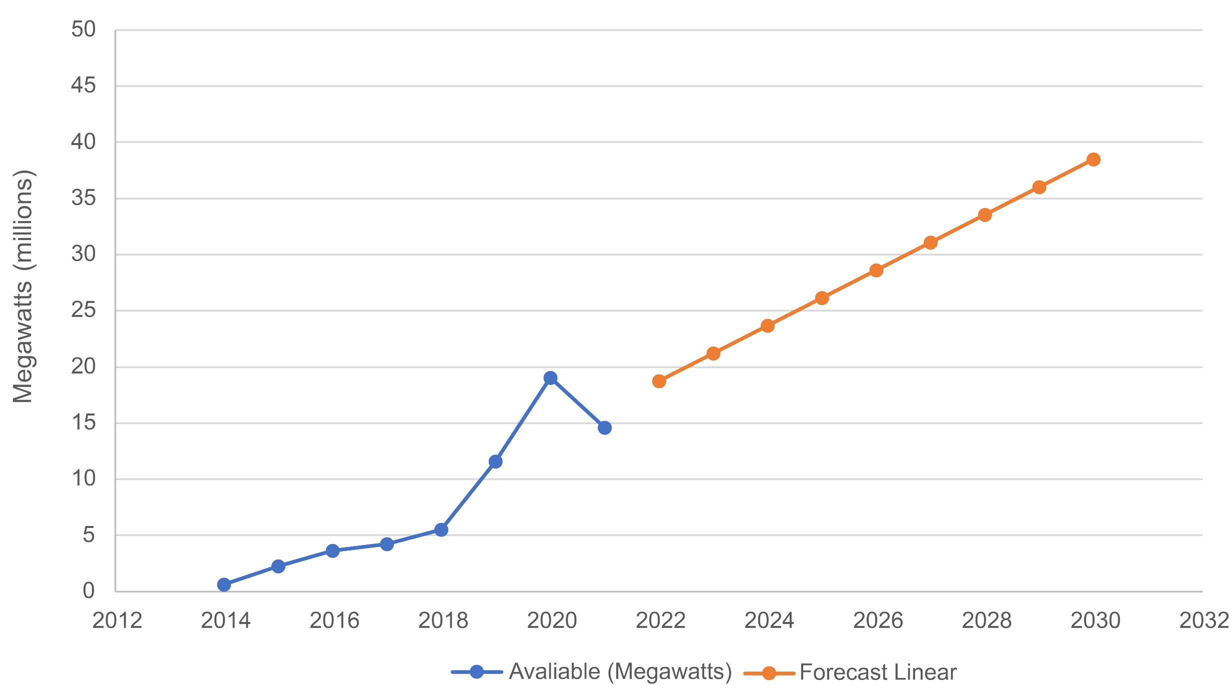


Since power curtailments are seasonal, the amount of hydrogen that can be produced from curtailed power is lower during certain parts of the year. More hydrogen can be produced in the spring than in other parts of the year. Due to this seasonality, if curtailed power becomes a major source of hydrogen generation, either a long-term storage solution will be needed to store excess hydrogen for later uses, or other sources of green energy will need to be procured so electrolyzers can continue to produce power during times when curtailed power availability is lower.

The availability of hydrogen generation would highly depend on infrastructure and storing capacity. Low-carbon hydrogen generation could also be used to engage with the demand response policy program by considering the time-of-use and demand response program by utility providers.

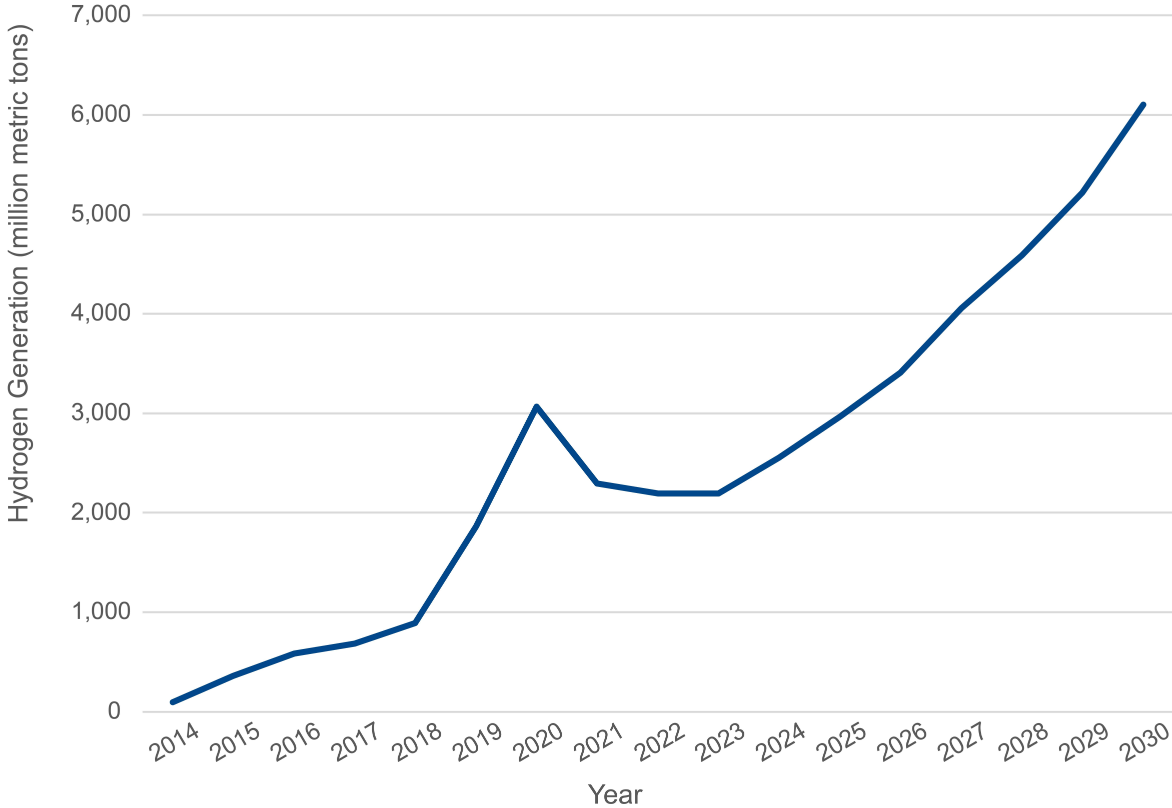
Using CAISO data, Figure E-2 projects future curtailment for 2023–2030.

Figure E-2. Projected Solar and Wind Power Curtailment



Based on this analysis, production can reach more than 600 million metric tons of hydrogen per year by 2030, as shown in Figure E-3 below.

Figure E-3. Hydrogen Potential from Curtailed Power



Appendix F. Hydrogen Demand

CALSTART projected hydrogen demand from 2022 to 2045 using the projections for the low-uptake scenario (133,458 Class 8 FCETs by 2045) and the high-uptake scenario (167,255 Class 8 FCETs by 2045). CALSTART calculated the cumulative FCET sales in each year and then calculated the hydrogen consumed per day for each FCET. Each truck was assumed to use about 48 kg per day (based on 6.2 miles per kg, 300 miles per day). Daily hydrogen consumption was multiplied by cumulative FCET deployments to calculate hydrogen demand in each year.

It is important to note that there are other types of commercially available FCEVs. These vehicles, which include FCEBs and light-duty vehicles, will also consume hydrogen. CALSTART projected how much hydrogen these non-truck vehicles would consume. Using data from CALSTART's *California Transit Agencies Chart a Course to Zero Emissions* report, CALSTART calculated the number of FCEBs that will be deployed each year between 2021–2045, assuming that each bus will use 20 kg of hydrogen per day [Paddon, 2021]. Actual hydrogen consumption from FCEBs may be higher than these projections. Some transit agencies have not declared whether they will use BEBs or FCEBs. Furthermore, not every transit agency has submitted their rollout plans as required by the Innovative Clean Transit regulation. This is especially true for small transit agencies, which do not have to submit until 2023. If any of these agencies end up purchasing FCEBs, they were not counted in CALSTART's report.

It is very likely that new types of FCEVs will emerge in the future. DOE awarded funding to multiple OEMs to develop MD fuel cell electric Class 4–6 trucks through the SuperTruck 3 program [DOE, 2021]. Since these vehicles are not commercially available and are in an earlier stage of technology development, this analysis did not consider hydrogen demand from these vehicles. CALSTART also did not include hydrogen demand from light-duty vehicles in this analysis.

CALSTART also compared hydrogen demand to projections for hydrogen production capacity and hydrogen refueling station capacity in 2024. Hydrogen production capacity was calculated according to the methodology in **Appendix D. Hydrogen Production**. Hydrogen refueling station capacity was determined by interviewing hydrogen providers, conducting desk research on hydrogen stations, and requesting public records of hydrogen stations that were funded by the State of California.

Appendix G. First-Mover Clusters

CALSTART projected hydrogen demand for the first-mover clusters. This calculation is similar to the methodology used in Appendix A and Appendix F. CALSTART used CARB's Large Entity Reporting data to estimate the number of vehicles domiciled in each cluster.[55] Large Entity Reporting data is aggregated by Air Basin. CALSTART used this data to estimate the number of day cab and sleeper cab tractors that currently exist in each cluster. Each cluster corresponds with a particular Air Basin.

- The Los Angeles-Orange County-Inland Empire Cluster corresponds with the South Coast Air Quality Management District.
- The Bay Area Cluster corresponds with the Bay Area Air Quality Management District.
- The Central Valley/SR-99 Cluster corresponds with the San Joaquin Valley Air Pollution Control District, the Sacramento Metro Air Quality Management District, and the Yolo-Solano Air Quality Management District.
- The San Diego Cluster corresponds with the San Diego County Air Pollution Control District.

The number of day and sleeper cab tractors in each cluster was used as the basis for calculating the FCET market opportunity for each cluster. This figure was calculated using the methodology described in Appendix A. The FCET market opportunity in each cluster was then used to calculate hydrogen demand in each cluster using the methodology described in Appendix F. The results of this analysis are included in Figures G-1 through G-4 below.

[55] CALSTART used the Large Entity Reporting dataset to conduct this analysis, specifically the Air Basin Aggregated data. This data can be found at https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks/large-entity-reporting.

Figure G-1. Los Angeles-Orange County-Inland Empire Cluster Hydrogen Demand

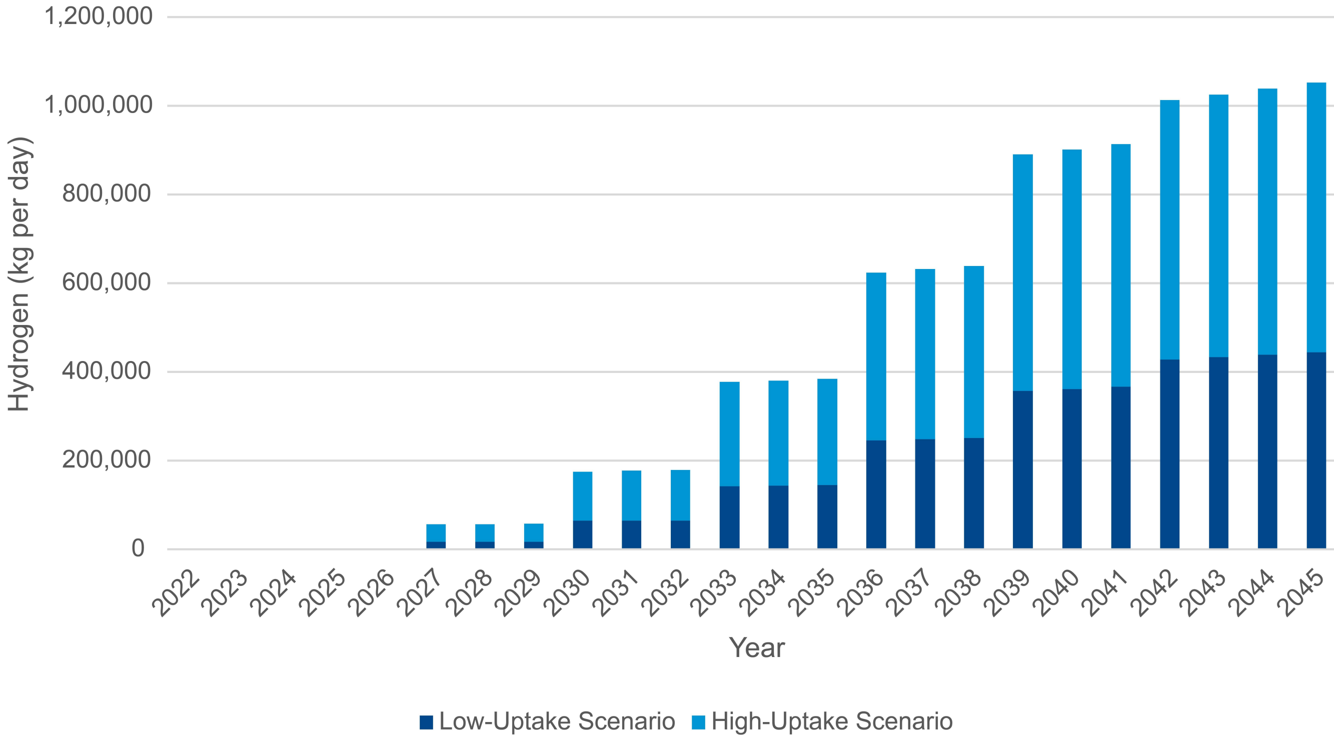


Figure G-2. Bay Area Cluster Hydrogen Demand

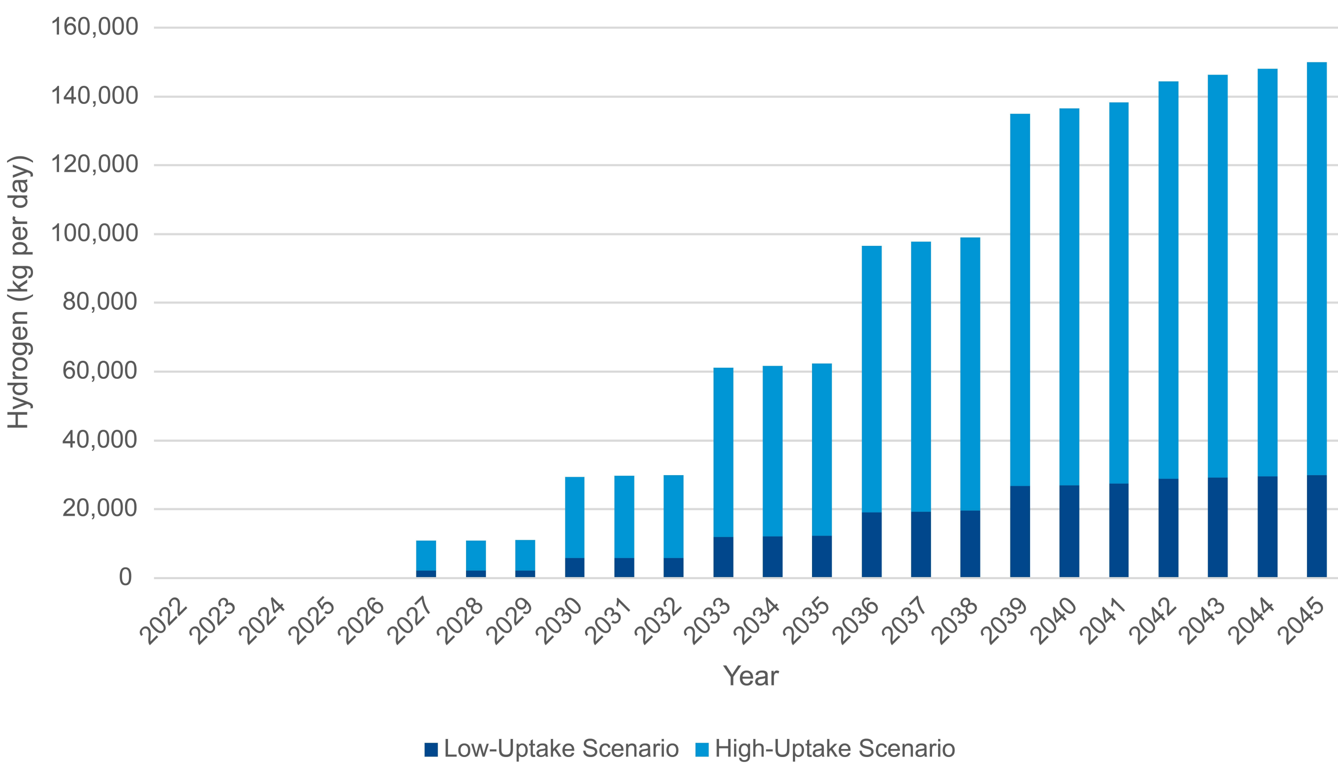


Figure G-3. Central Valley/SR-99 Cluster Hydrogen Demand

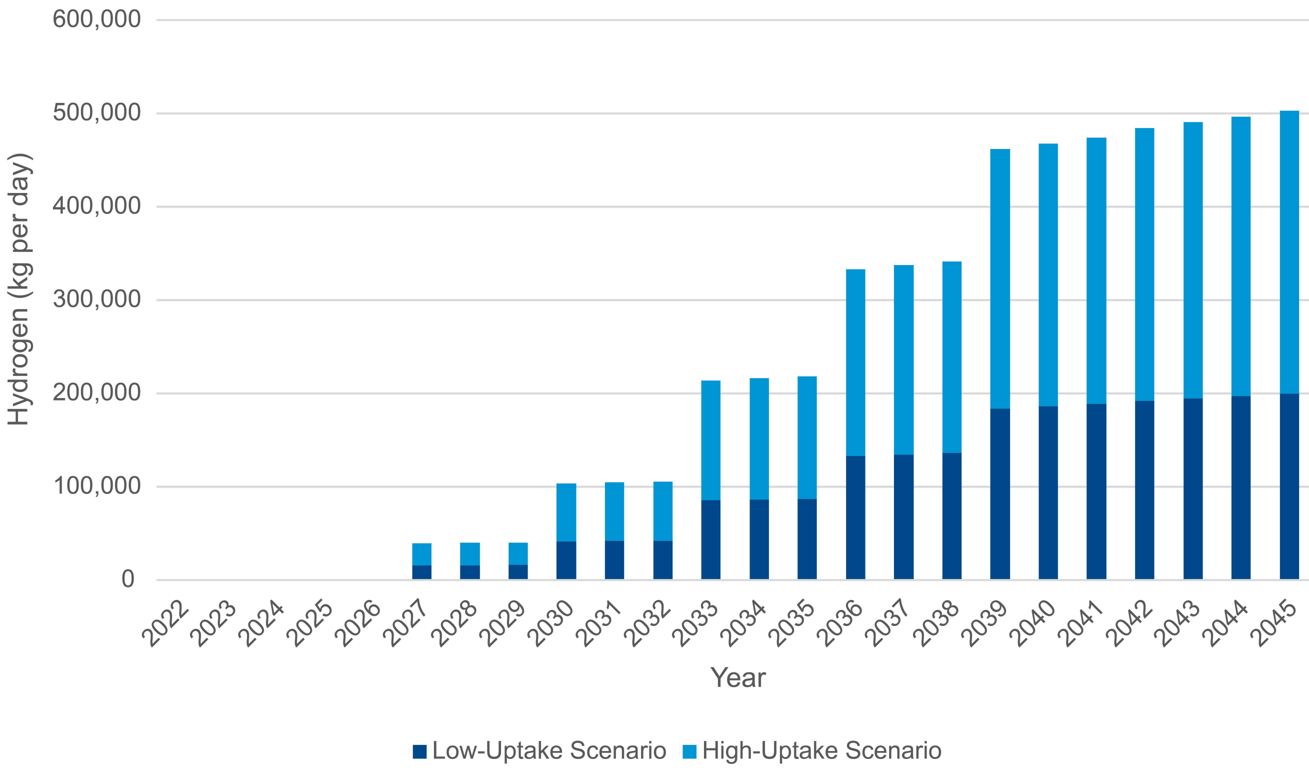
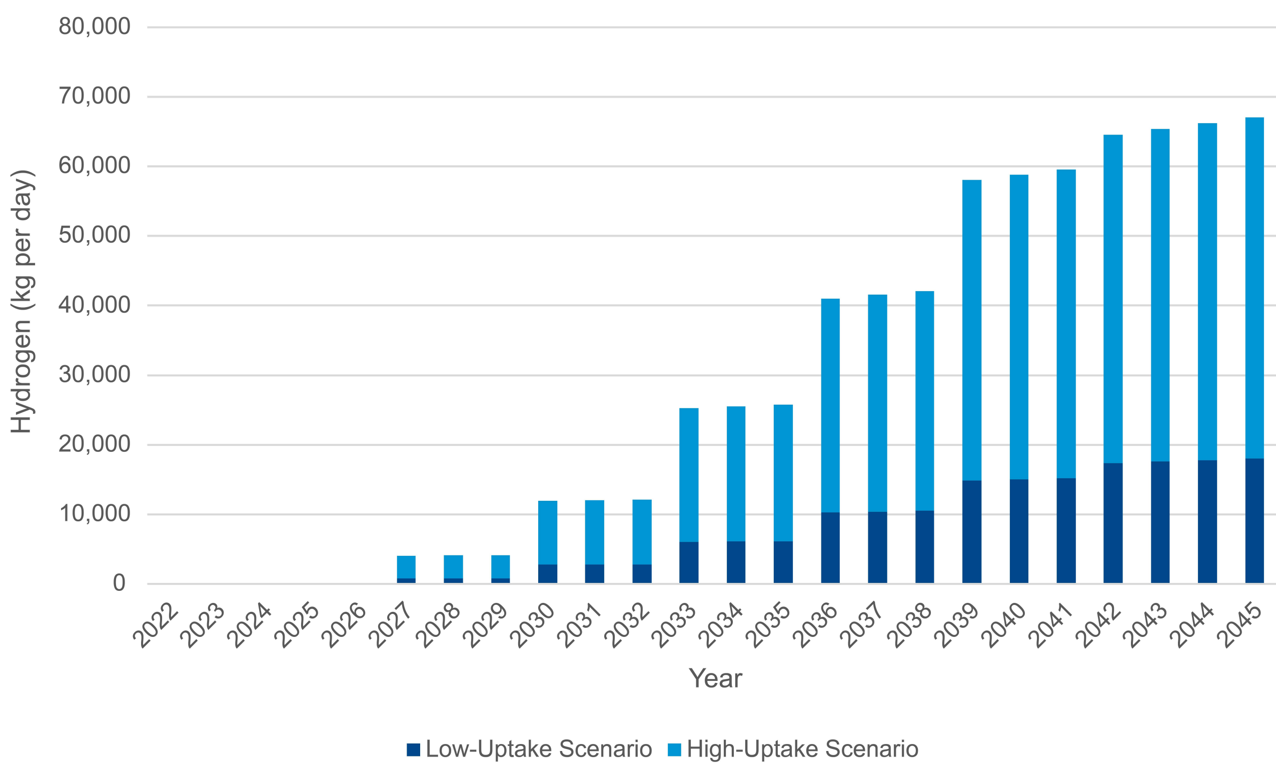


Figure G-4. San Diego Cluster Hydrogen Demand



This methodology calculated hydrogen demand for vehicles based in these clusters. Since these clusters are major generators of freight traffic, FCETs originating from outside of the cluster will need to fuel. As a result, the hydrogen demand figures should be viewed as the minimum requirements for each cluster.

CALSTART also calculated the number of stations required to serve each cluster. CALSTART calculated the difference between projected hydrogen demand and the hydrogen fueling capacity in each cluster. CALSTART assumed that future stations will have a capacity of 5,000 kg per day. As a result, the difference between hydrogen demand and fueling capacity was divided by 5,000 to calculate the minimum number of stations.

Appendix H. Retail Hydrogen Costs

CALSTART conducted this analysis to understand retail hydrogen costs and project future retail hydrogen prices. The cost of retail hydrogen was broken down into several components, including cost of hydrogen production, cost of distributing and transporting the hydrogen to the station, levelized cost of the hydrogen station equipment, levelized cost of constructing the hydrogen station, and OPEX associated with operating the station.

CALSTART also analyzed the current breakdown of retail hydrogen prices. According to the DOE's Hydrogen Earthshot Program, the production cost of hydrogen is $5.00 per kg [DOE, n.d.]. In addition, CALSTART used the parameters provided by Shell for the remaining cost components [Munster, 2018]. The assumptions used in this analysis are displayed in Table H-1.

Table H-1. Assumptions for Current Retail Hydrogen Price Breakdown

Component	Levelized Cost per kg of Hydrogen	Source
Hydrogen Production	$5.00	DOE, n.d.
Hydrogen Distribution	$1.50	Munster, 2018
Levelized Hydrogen Station CAPEX	$3.75	Munster, 2018
Levelized Construction Costs	$1.04	Munster, 2018
OPEX	$2.69	Munster, 2018

Retail hydrogen prices are expected to decrease as volumes increase and as the hydrogen supply market becomes more competitive. CALSTART projected retail hydrogen prices in the future and created three scenarios. Under Scenario 1, the production cost of hydrogen and the construction cost remain the same. However, the cost of hydrogen distribution, the hydrogen station, and OPEX decreases. These prices for hydrogen distribution and OPEX were assumed to follow market projections provided by Shell [Munster, 2018].

The cost of the hydrogen station CAPEX was calculated using the Learning Rates methodology discussed in Appendix C. CALSTART conducted learning rate analysis to determine how economies of scale will impact the price of hydrogen station components. CALSTART's analysis for hydrogen fueling stations focused on major components in a fueling station, including compressors, dispensers, stationary hydrogen storage tanks, and other components. This analysis was used to project how much the cost of a hydrogen station will fall.

CALSTART used the learning rates methodology to understand how the price of each component would decrease as economies of scale are achieved. CALSTART used hydrogen station fueling capacity as the metric for economies of scale and assumed that fueling capacity will reach 3.2 million kg of hydrogen per day (i.e., the amount of hydrogen fueling capacity required to fuel all FCETs under the high-uptake scenario). CALSTART calculated the reduction in the cost of each individual component. Each component's cost reduction was weighted based on its contribution to the overall cost of the station. This was then used to calculate the overall cost reduction for the station. Based on these assumptions, CALSTART determined that the hydrogen station CAPEX cost decreases by 21.58% when economies of scale are reached. The parameters used for this calculation are displayed below in Table H-2, and the results of this analysis are displayed below in Figure H-1.

Table H-2. Learning Rates for Hydrogen Station Components

Hydrogen Station Component	Learning Rate[56]	Contribution to Overall Hydrogen Station Cost[57]
Compressors	5%	36.5%
Dispenser	4%	11%
Stationary Hydrogen Storage Tanks	2%	47%
Other Components	10%	5.5%

[56] Based on data from Ruffini, 2018.
[57] Based on the solicitation that Shell submitted to GFO-20-606.

Figure H-1. Component Contribution to Hydrogen Station Cost

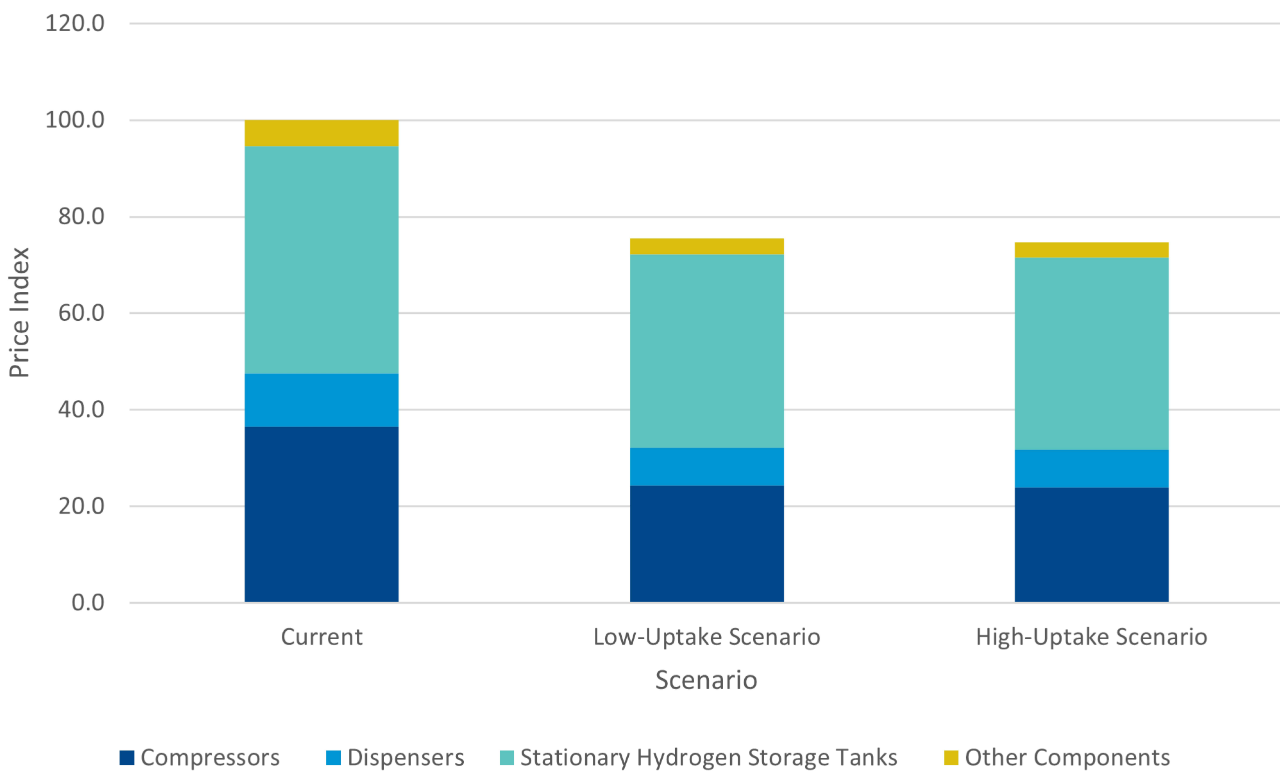


Table H-3 includes the assumptions for Scenario 1.

Table H-3. Assumptions for Scenario 1 Retail Hydrogen Price Breakdown

Component	Levelized Cost per kg of Hydrogen	Source
Hydrogen Production	$5.00	DOE, n.d.
Hydrogen Distribution	$0.60	Munster, 2018
Levelized Hydrogen Station CAPEX	$2.94	Learning Rates methodology
Levelized Construction Costs	$1.04	Munster, 2018
OPEX	$1.48	Munster, 2018

Scenario 2 (Table H-4) combines Scenario 1 with decreases in hydrogen production cost. Under this scenario, the DOE Hydrogen Earthshot objective of hydrogen production costs of $1 per kg is achieved.

Table H-4. Assumptions for Scenario 2 Retail Hydrogen Price Breakdown

Component	Levelized Cost per kg of Hydrogen	Source
Hydrogen Production	$1.00	DOE, n.d.
Hydrogen Distribution	$0.60	Munster, 2018
Levelized Hydrogen Station CAPEX	$2.94	Learning Rates methodology
Levelized Construction Costs	$1.04	Munster, 2018
OPEX	$1.48	Munster, 2018

Scenario 3 (Table H-5) combines Scenario 2 with incentives for hydrogen station equipment. Under this scenario, the station owner receives an incentive equal to half the cost of the hydrogen station equipment, effectively decreasing the cost of hydrogen station by 50%. This 50% incentive corresponds with the incentives provided by the EnergIIZE program.

Table H-5. Assumptions for Scenario 3 Retail Hydrogen Price Breakdown

Component	Levelized Cost per kg of Hydrogen	Source
Hydrogen Production	$1.00	DOE, n.d.
Hydrogen Distribution	$0.60	Munster, 2018
Levelized Hydrogen Station CAPEX	$1.47	50% reduction from Scenario 2
Levelized Construction Costs	$1.04	Munster, 2018
OPEX	$1.48	Munster, 2018

Impact of Inflation Reduction Act and RIN Credits

CALSTART also projected the impact that the Inflation Reduction Act will have on the price of retail hydrogen prices. CALSTART examined two policies enacted under the Inflation Reduction Act. These policies are the Hydrogen Production Tax Credit and the Alternative Fuel Vehicle Refueling Property Credit. The Hydrogen Production Tax Credit provides a tax credit of up to $3.00 per kg, depending on the production pathway. CALSTART assumed a production tax credit of $0.75. This credit corresponds to hydrogen produced via electrolysis. CALSTART assumed that the entire benefit of the tax credit will be passed on to the customer, and the $0.75 production tax credit was subtracted from the Scenario 3 price.

CALSTART also modelled the Alternative Fuel Vehicle Refueling Property Credit. This credit provides a tax credit equal to 30% of the cost of any qualified alternative fuel vehicle refueling property placed in service. CALSTART modeled this policy by reducing the Levelized Hydrogen Station CAPEX under Scenario 3 by 30%. This analysis assumes that the entire benefit of the tax credit is passed on to the customer.

CALSTART also proposed that low-carbon hydrogen be awarded RIN credits. CALSTART modelled the price of RIN credits by calculating the average cost per RIN credit between January–October 2022. RINs are awarded according to the energy content equivalent of a gallon of propane equivalent. A kg of hydrogen has approximately the same energy content as a gallon of biodiesel [EPA, 2022a]. The price of the RIN credit was multiplied by 1.5 to obtain the kg of hydrogen price equivalent (Table H-6).

Table H-6. RIN Credits Hydrogen Equivalent

RINs Pathway	Average Cost per RINs Credit (January–October 2022)	Kg of Hydrogen Equivalent
D-5	$1.63	$2.45
D-6	$1.32	$1.98

CALSTART used the RIN pricing for the D-6 pathway as a conservative estimate of the value of RIN credits. The value of the RIN credits was subtracted from the hydrogen price calculated under the Inflation Reduction Act scenario.

Appendix I. Interview Methodology

CALSTART gathered data for this project by engaging with entities in the FCET industry. CALSTART conducted interviews with fleets that operate Class 8 trucks and with hydrogen infrastructure providers. All interviews were held in 2021. Interviews were semi-structured. Details about the interviews are included below.

Fleets

CALSTART conducted interviews with fleets to gather data on their baseline operations, as well as on each fleet's openness to adopting ZETs. Interviews were semi-structured. The key themes that CALSTART sought to understand are listed below.

- Truck duty cycles and baseline operations
- Composition of the fleet
- Truck refueling operations
- Truck depot locations
- Previous experience with clean transportation technology such as CNG trucks
- Openness to adopting ZETs
- Preference between adopting BETs and FCETs
- Barriers to adopting FCETs

The fleets that CALSTART interviewed are listed below.

- Air Products
- FedEx Express
- HACTI (Hyundai)
- JB Hunt
- Pasha Net Drayage
- Quick Pick Express
- Ramsey Xpress
- Trimodal
- UPS
- US Foods
- US Postal Service

Hydrogen Infrastructure Providers

CALSTART also conducted interviews with hydrogen infrastructure providers. This sector is broad and includes hydrogen producers, hydrogen station developers, and hydrogen equipment companies. Hydrogen producers include industrial gas companies and smaller hydrogen production companies. Hydrogen station developers include companies that build and operate hydrogen stations as well as truck stops that are interested in hosting hydrogen stations. The hydrogen equipment category includes companies that produce either hydrogen production or hydrogen station equipment. Many companies have operations in more than one of these categories. CALSTART restricted this analysis to companies that plan to provide hydrogen to the California market. CALSTART conducted semi-structured interviews with these stakeholders to understand the market for hydrogen.

Key themes that CALSTART explored during interviews with hydrogen producers are listed below.

- Existing hydrogen production capacity
- Current plans for scaling up hydrogen production
- Projected market demand for hydrogen
- Hydrogen production pathways
- Hydrogen delivery and distribution methods
- Factors influencing future investment in hydrogen production
- Policies to encourage and incentivize hydrogen production

Key themes that CALSTART explored during interviews with hydrogen station developers are listed below.

- Existing hydrogen stations deployed or in development
- Current plans to deploy additional hydrogen fueling stations
- Comparison of equipment needs for light-duty stations and MHD stations
- Hydrogen station economics and business models
- Barriers to deploying hydrogen fueling stations
- Leadtime for building and commissioning a new hydrogen station
- Factors influencing future investment in hydrogen station development
- Policies to encourage and incentivize hydrogen station development

Key themes that CALSTART explored during interviews with hydrogen equipment manufacturers are listed below.

- Technical specifications of hydrogen equipment
- Equipment reliability statistics
- Hydrogen equipment technology development
- Leadtime for deploying hydrogen equipment
- Regulatory environment for hydrogen equipment
- Hydrogen equipment economics and business models

The hydrogen infrastructure providers that CALSTART interviewed are listed below.

- Air Liquide
- Air Products
- Bayotech
- BP Hydrogen
- Clean Energy Fuels
- First Element Fuels
- Iwatani
- Linde
- Loves Travel Stops & Country Stores
- Nel Hydrogen
- NextEra Energy
- Nikola
- OneH2
- Plug Power
- Powertech Labs
- Shell
- Travel Centers of America