Transportation White Paper

Written in collaboration with
ARCHES Transportation Working Group

October 2024

ARCHES H2

Acknowledgements

Thank you to Dr. Lewis Fulton from UC Davis Institute for Transportation Studies and Jaimie Levin from Center for Transportation and the Environment for their leadership as Co-Chairs of the ARCHES Transportation Working Group and their important role as lead authors of this paper along with Diane Moss from the Renewables 100 Policy Institute. ARCHES would also like to thank the Working Group participants for their time, collaboration and participation. Your input throughout the process is greatly appreciated. Please see Appendix C for a list of participants and their affiliation.

Foreword

The Alliance for Clean Hydrogen Energy Systems, ARCHES, is California's initiative to accelerate renewable, clean hydrogen projects and infrastructure. California has a pivotal opportunity to decarbonize important sectors of the state's economy, towards achieving the State's ambitious greenhouse gas reduction goals. Through ARCHES, California can play a decisive role in realizing the U.S. Department of Energy's Hydrogen Earthshot target of lowering clean hydrogen production costs five-fold to $1 per kilogram ($1/kg) within a decade.

New technology and large-scale deployment will be needed to achieve these goals. Clean hydrogen made from renewable sources, ranging from renewably powered electrolysis to agricultural biomass, offers enormous promise to advance a zero-carbon economy and to reduce the costs of clean hydrogen. Innovative electrolysis and fuel cell technologies as deployed through ARCHES can help decarbonize sectors like heavy-duty freight, shipping, ports, and energy generation and offer the promise of cleaner air for all communities and new good jobs. To this end, in late 2022, ARCHES commissioned a series of white papers spanning multiple thematic working groups meetings convened topically, and across sectors, charged with developing a clean hydrogen roadmap and blueprint to inform, stimulate and scale up clean hydrogen activities across California.

Drawing upon the knowledge and expertise of academic, government, industry, nonprofit, and labor representatives, the ARCHES Clean Hydrogen White Papers are the culmination of over two years of regular meetings. Each white paper is co-authored by a Working Group Chair from the University of California, with two or more co-chairs and/or facilitators, with contributions from working group members. Key recommendations that would support overall development of a clean hydrogen economy include:

- Coordinate an **aligned state and federal definition of clean hydrogen**
- Devise hydrogen pricing programs that ensure **transparency, consistency, longevity, and adaptability**
- Develop hydrogen **transportation and storage infrastructure for both gas and liquid**
- Ensure that local, state and federal agencies that oversee emissions, safety, and permitting generate **aligned and adaptable standards and regulations and**
- Promote **collaboration and communication among stakeholders**, including communities, industries, regulatory agencies, and workforce development programs

Table of Contents

Executive Summary

The use of hydrogen and fuel-cell technology in California's transportation sector will be crucial to achieve the zero-emission transportation goals of the State of California, along with federal goals to reduce transportation emissions.[1] The following summary outlines top findings by the ARCHES Transportation Working Group, identifying the opportunities and challenges related to achieving a mature hydrogen transportation market in California with a primary focus on the medium- and heavy-duty fuel cell electric vehicle (FCEV) market.

Opportunities

Alignment with State Priorities

FCEVs provide a pathway to zero-emissions for the medium- and heavy-duty (MDHD) transportation sector where batteries alone may fall short.[2] FCEVs can achieve this while still supporting vital truck and bus operational requirements, such as driving range, payloads equivalent to diesel trucks, refueling time, and continued operations during grid outages. Replacing diesel trucks with zero-emission fuel-cell electric trucks (FCETs) will dramatically cut criteria pollutant emissions in Justice40 communities, also known as disadvantaged communities, reducing one of the biggest sources of negative health impacts from conventional transportation and energy systems.[3][4]

Cost of Ownership Parity

Matching hydrogen FCEVs to diesel vehicles on total cost of ownership (TCO) can happen once clean hydrogen cost targets are met, and FCEV purchase costs begin to match conventional vehicles as production and supply chain volumes expand. A wide range of manufacturers have launched or are preparing to launch heavy duty FCEV models at commercial scale, particularly Class 7 and 8 heavy-duty trucks. Transit agencies are recognizing that fuel-cell electric buses (FCEBs) can be cost competitive

---

[1] White House, "Biden-Harris Administration Proposes New Standards to Protect Public Health that Will Save Consumers Money, and Increase Energy Security," April 2023, https://www.whitehouse.gov/briefing-room/statements-releases/2023/04/12/fact-sheet-biden-harris-administration-proposes-new-standards-to-protect-public-health-that-will-save-consumers-money-and-increase-energy-security/

[2] CALSTART, *Roadmap to Fuel Cell Electric Truck Commercialization*, March 2023, https://calstart.org/wp-content/uploads/2023/03/Roadmap-to-FCET-Commercialization.pdf

[3] ARCHES Health Model, LBNL, April 2023, projects $2.95B in annual health savings, mostly driven by replacing 5500 Class 6-8 Trucks and 1,000 CNG buses with hydrogen fuel cells trucks and buses.

[4] Executive Office of the President, M-23-09, 2023, https://www.whitehouse.gov/wp-content/uploads/2023/01/M-23-09_Signed_CEQ_CPO.pdf

with the potential to replace conventional internal combustion engine buses one-for-one without sacrificing performance and operational efficiencies. New FCEB models available in 2025 will provide 350 miles or more of driving range. As with all new technologies, more options for end-users mean greater competition among manufacturers and more robust and mature supply chains, which can drive down costs.

Driving Demand

MDHD FCEV market development will greatly expand demand for hydrogen production, efficient distribution, storage and supply, and refueling infrastructure. Infrastructure investments and knowledge gained through developing these vehicles and stations can be further leveraged for other transportation applications, such as rail, heavy-use urban vehicles such as refuse trucks, off-road heavy equipment at ports and airports, aviation, and maritime applications. This should also promote growth in the light duty FCEV market and accelerate station technology improvements across vehicle classes.

Challenges and How to Address Them

Timeline and Incentives

To support widespread adoption, FCEBs and FCETs must become cost-competitive with conventional trucks and buses in the next few years, including both upfront capital and ongoing operational costs (i.e., similar TCO). Until cost targets are met, policies supporting cost reduction are needed. To build confidence throughout the transition to these new technologies, fleets require incentives that are predictable, easy to access, and focused on areas that accelerate adoption. This will build market certainty for manufacturers to invest in large-scale production and establish service centers, ultimately leading to a robust secondary market. A comprehensive plan, leveraging ARCHES' unique systems level position, can help deliver the necessary confidence. This could include establishing the Medium- and Heavy-Duty Zero-Emission Vehicle Fleet Purchasing Assistance Program, mandated in SB 372 (Leyva, Chapter 639, Statutes of 2021), which would help reduce upfront costs and financing hurdles for FCETs. Reducing or eliminating sales tax for zero-emission trucks and buses, and an exemption of the 12% Federal Excise Tax on zero-emission trucks, would further reduce costs for end-users.

Furthermore, a program to guarantee the residual value of a FCET would remove a write-down risk for the large fleet that purchases the new vehicle, while providing access to secondary market vehicles that dealers could resell to smaller fleets and independent operators who could benefit from the lower price tag of a used FCET. Bulk purchases of standardized FCEBs, e.g. via state contract pricing for guaranteed larger volumes, would ensure larger production volumes of a standard design for manufacturers and better supply-chain pricing. However, unless and until the federal government bridges the significant price gap between FCEBs and conventional internal combustion engine buses for all procurements, additional subsidies will need to be provided by the state to make FCEBs affordable for transit agencies.

Bringing Down the Cost of Hydrogen for the MDHD Transportation Sector

To achieve operational costs for FCETs and FCEBs that are comparable with diesel, hydrogen fuel retail price needs to reach $5-6/kg or less.[5] Federal and state incentives, along with a robust ARCHES hydrogen marketplace, can help fleets feel confident they will have a consistent and affordable hydrogen supply as they make a commitment to purchase FCETs and FCEBs. California is uniquely positioned to drive down the cost of renewable clean hydrogen with the California Air Resources Board's (CARB) well established Low Carbon Fuel Standard (LCFS), which is crucial to meeting our climate goals in an economically efficient manner. Further refinements, including allowing LCFS Hydrogen Refueling Infrastructure credits for stations that serve MDHD FCEVs, can help accelerate the clean hydrogen market. At the federal level, the IRS 45V production tax credit will provide a set incentive for clean hydrogen producers to reduce prices for end users, as would expansion of U.S. Environmental Protection Agency Renewable Identification Number credits for hydrogen. Mechanisms that build transparency, longevity, consistency, and adaptability into hydrogen production pricing incentive programs will encourage sustained investment and support market development. Establishing statewide vehicle, station, clean hydrogen supply, and pricing goals for 2031, e.g. through the SB 643 (Archuleta, Chapter 646, Statutes of 2021) report and the Hydrogen Market Development Strategy, would also help build certainty among manufacturers, fuel producers, and end users. Creating a fuel supply exchange, managed by ARCHES, could additionally match producers with price incentives and enable fleet operators and station providers to obtain the lowest price possible for their fuel while maintaining a robust and sustainable supply.

Refueling Infrastructure

Fleets that operate "over the road" trucks need to access sufficient fuel for their FCETs in convenient locations and in a timely manner to maintain operational efficiency. Freight infrastructure roadmap efforts, such as the California Transportation Commission (CTC) SB 671 Working Group and the National Zero-Emission Freight

---

[5] U.S. Department of Energy, *National Clean Strategy and Roadmap (Draft)*, September 2022 https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/clean-hydrogen-strategy-roadmap.pdf?Status=Master

Corridor Strategy, must be aligned and projects must be implemented promptly. The California Energy Commission (CEC) Energy Infrastructure Incentives for Zero-Emission (EnergIIZE) Commercial Vehicles, CEC's Charging and Refueling Infrastructure for Transport in California Provided Along Targeted Highway Segments (CRITICAL PATHS) 2.0, and the U.S. Department of Transportation's Infrastructure Investment and Jobs Act (IIJA) Alternative Fuels Corridor Funding should focus on priority projects identified in these roadmaps.

Station planning, permitting, and construction need to be streamlined to dramatically reduce station implementation timelines, similar to what has been done in California for electric vehicle charging stations. There are several opportunities for advancing this goal: the California Public Utilities Commission (CPUC) is conducting an energization timelines rulemaking that could help accelerate projects like hydrogen refueling stations that are needed to accomplish state zero emissions and climate targets, the Governor's Office of Business & Economic Development (GO-Biz) plans to update its Hydrogen Station Permitting Guidebook to reflect new legislation and lessons learned, and the Governor's Infrastructure Strike Team is focusing administration efforts on getting projects in the ground.[6,7,8] Success of these and other initiatives hinges on contributions from groups building the infrastructure and recognition by regulators of the critical role hydrogen stations stand to play in decarbonizing and eliminating emissions from trucks, buses, and fleets. Along similar lines, all hydrogen refueling stations and vehicle systems must be widely compatible, both within and outside California, and able to handle peak dispensing demands. Mobile refueling can serve as a bridge technology to encourage early adoption of heavy-duty FCEVs while permanent refueling stations are being built. Hydrogen fueling and fuel quality standards must be fully integrated into existing regulatory oversight structures to protect end-users and ensure a level playing field in the nascent hydrogen market.

Achieving Economies of Scale

Heavy-duty vehicle manufacturers need to produce vehicles in greater volumes to achieve economies of scale and reduce costs to customers. Fleets must have a variety of models available to meet different operational needs. Predictable government support mechanisms to ensure incentives will be available for a minimum number of

---

[6] California Public Utilities Commission, *Energization,* https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/infrastructure/energization

[7] Governor's Office of Business and Economic Development, *Hydrogen Fueling Station Readiness,* *https://business.ca.gov/industries/zero-emission-vehicles/hydrogen-readiness/*

[8] State of California, *Building California's Future*, https://build.ca.gov/

vehicles, e.g. at least 5,000 FCETs and 1,000 FCEBs in California, with other markets developing around the country, should help companies invest in the manufacturing infrastructure and supply chain contracts necessary to build vehicle production volume and diversify their product offerings. Clustering deployments of 100 to 500 trucks regionally within corridors would enable vehicle and station manufacturers to focus fueling, maintenance, and repair services effectively, thereby reducing costs. Increasing California's road weight limits for FCETs, which currently weigh more than diesel vehicles, would enable them to carry the same loads as diesel vehicles, improving profitability and encouraging sales.

Section 1: Sector Overview

ARCHES aims to help establish a self-sustaining market for hydrogen FCEVs, particularly MDHD vehicles, with a view toward catalyzing hydrogen adoption for other applications. A successful launch of MDHD FCEVs will help California on its path to 100% zero-emission transportation and support federal actions to reduce transportation emissions. The ARCHES Transportation Working Group (TWG) identified the opportunities, challenges, and recommended policy actions related to achieving a mature hydrogen transportation market in California, with a primary focus on the MDHD FCEV market.

1.1. Transportation Sector Overview

While there are 30 million light-duty (LD) vehicles of all fuel types in California, there are fewer than one million trucks. Around 250,000 of them are Class 7-8 trucks, a primary focus for the transportation element of the ARCHES hydrogen hub. There are more than 100 transit agencies in the state, with a combined fleet of more than 18,000 buses, trains, and other support vehicles. Roughly 10,500 transit buses directly operate in Justice40 communities, where emissions from conventional buses fueled by diesel and natural gas have a negative impact on public health. California has been a frontrunner in adopting policies to transition the state's vehicles to zero-emissions. FCEVs are one of the two types of zero-emission technology needed to ensure clean air for California and beyond.[9,10,11,12]

1.2. Current Role of Hydrogen in Transportation

Around 3,784 zero-emission MDHD vehicles were operating in California in 2023.[13] As of July 2024, FCETs commercially operating on North American roads include 30 Hyundai heavy-duty (HD) trucks delivered for the NorCal Zero project at the Port of Oakland, and 112 Nikola HD trucks.[14] California's Hybrid and Zero-Emission Voucher Incentive Project (HVIP) publishes a list of trucks that qualify for funding and now includes six fuel cell models, mainly in the HD class.[15] The DOE Alternative Fuel Data Center's Alternative Fuel and Advanced Vehicle Search currently lists a total of seven commercially available MDHD FCEV models, including three buses with passenger capacities between 43 and 73 people, one cargo truck, a Class 7 street sweeper truck, and two Class 8 trucks with 450 and 500 miles of range.[16] Other models in other market classes are in development.

While FCEBs still represent a small portion of the total bus fleet, and only a handful of transit agencies have deployed FCEBs, the successful performance of those vehicles, and the relative ease of fueling them, has significantly raised interest among other agencies. In 2018, only three transit agencies indicated the desire to purchase FCEBs in

---

[9] State of California, *Executive Order N-79-20*, September 2020, https://www.gov.ca.gov/wp-content/uploads/2020/09/9.23.20-EO-N-79-20-Climate.pdf *requires 100% of in-state sales of new passenger vehicles and drayage trucks to be zero-emission by 2035, with MDHD vehicles to follow in 2045.*

[10] CARB, *Advanced Clean Trucks*, https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks *requires increasing percentages of various classes of truck sales to be zero-emission options from 2024-2035.*

[11] CARB, *Innovative Clean Transit (ICT)*, May 2019, https://ww2.arb.ca.gov/resources/fact-sheets/innovative-clean-transit-ict-regulation-fact-sheet. Requires public transit fleets to start switching from conventional buses with internal combustion engines to zero-emission buses in 2023 and all transit buses in California to be zero-emission by 2040. Full implementation of this regulation is expected to reduce GHG by 19 million metric tons from 2020 to 2050 – the equivalent of taking 4 million cars off the road. The ICT will reduce harmful tailpipe emissions (nitrogen oxides and particulate matter) by about 7,000 tons and 40 tons respectively during that same 30-year period.

[12] Advanced Clean Fleets Regulation (2023) requires manufacturers of MDHD vehicles for fleets performing drayage operations, those owned by government agencies, and high priority fleets to sell only zero-emission MDHD vehicles for these applications starting in 2026 and for these fleets to transition to all zero-emission between 2024 and 2035, depending on the type of fleet.

[13] California Energy Commission, *Medium- and Heavy-Duty Zero-Emission Vehicles in California*, https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-and-infrastructure-statistics/medium-and-heavy

[14] See https://www.hyundai.com/worldwide/en/newsroom/detail/hyundai-motor-spearheads-u.s.-zero-emission-freight-transportation-with-norcal-zero-project-launch-0000000760; and https://www.nikolamotor.com/nikola-wholesales-72-hydrogen-fuel-cell-trucks-for-north-american-customers-in-q2-2024-exceeds-sales-guidance

[15] California HVIP, *HVIP Eligible Vehicles*, https://californiahvip.org/vehiclecatalog/

[16] U.S. Department of Energy, *Alternative Fuel and Advanced Vehicle Search*, https://afdc.energy.gov/vehicles/search/

their mandated Innovative Clean Transit plan submitted to CARB. In updates to those plans in 2023, however, 41 agencies with a combined fleet of 5,500 transit buses (40% of California's total fleet of buses) registered their intent to purchase FCEBs.[17]

While not a focus of ARCHES, the light duty vehicle market has been an important early adopter of hydrogen with 18,355 LD FCEVs leased or sold in California, by far the most in any state in the U.S.[18] Around seven models of LD FCEV are on the market, with one or two of these models to date dominating sales. Over the past few years, sales of LD FCEVs have grown more slowly, a trend due in part to hydrogen refueling limitations and high hydrogen prices. The state has been working to expand the 43 hydrogen refueling stations currently in operation to 200 in the next few years, with 86 stations funded and in development.[19] The sale of hydrogen for use in FCEVs is currently approximately 10-15 tons per day in California, and mainly serves the LD vehicle market.

Notably, hydrogen fuel for transportation is largely renewable, and hydrogen refueling has transitioned to renewable resources more quickly than battery electric charging. In 2020, an estimated 90% renewable content was achieved in hydrogen used for refueling in California. Although this dropped to around 50% in 2022, several operators were at or near 100% renewable content.[20]

1.3. Future Vision for Hydrogen in Transportation

Most FCETs sales over the next seven years are expected to be in the heavy-duty tractor-trailer or "straight truck" classes, rather than vocational or smaller delivery classes. Overall, we estimate that about 100,000 Class 7-8 trucks will be sold over this 7-year period. ARCHES' target of about 5,000 FCETs represents 5% of these total sales. The number of fleets that would purchase these trucks, the typical number of trucks per fleet, and the number of trucks produced by individual original equipment manufacturers (OEM), to achieve economies of scale, are open questions. One certainty is that strong support from fleets and OEMs is critical. The numbers needed to bring costs and prices to a competitive level will be tracked and refined over time when more fleet operators start to deploy FCETs.

---

[17] California Air Resources Board, *Innovative Clean Transit Regulations*, https://ww2.arb.ca.gov/our-work/programs/innovative-clean-transit/ict-rollout-plans

[18] Hydrogen Fuel Cell Partnership, *FCEV Sales, FCEB, & Hydrogen Station Data*, https://h2fcp.org/by_the_numbers

[19] Hydrogen Fuel Cell Partnership, *FCEV Sales, FCEB, & Hydrogen Station Data*, https://h2fcp.org/by_the_numbers

[20] California Air Resource Board, *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development*, December 2023,, https://ww2.arb.ca.gov/sites/default/files/2023-12/AB-8-Report-2023-FINAL-R.pdf

As mentioned above, many transit agencies are planning to continue or start operating FCEBs in California, indicating the potential for 1,000 FCEBs to be in operation by 2030. Looking ahead, FCEBs hold several advantages that could lead to further cost reductions and greater competitiveness. FCEBs use a battery that is less than 1/6 the size of a battery electric bus, while providing longer range, faster refueling, and consistent performance from full tank to empty, and from cold weather to hot. Fuel cells maintain the battery state of charge, reducing battery degradation and improving lifetime costs. According to a Foothill Transit analysis, operating 23 FCEBs with hydrogen refueling infrastructure over a 12-year period instead of battery electric buses would result in a savings of $12.9 million.[21]

A fleet of 5,000 trucks and 1,000 buses would use approximately 200-250 tons/day of hydrogen, based on estimated daily hydrogen use for different types of vehicles. This level of demand would be on the order of 20 times more than today's hydrogen demand for LD vehicles. Along with increased production of renewable hydrogen through ARCHES projects, this increased demand will put downward pressure on the hydrogen price for all end-users, including LD FCEVs.

The ARCHES vision for FCETs out to 2030 is part of a larger picture of expanded use of FCEVs of various classes and types, and we project many additional FCETs and FCEBs to be spurred by the ARCHES efforts, along with the adoption of 50,000 or more LD FCEVs. Coupled with the Advanced Clean Fleets regulation, ARCHES' support of HD FCEVs could unlock a market for tens of thousands of trucks by the early 2030s. ARCHES aims to spur such "multiplier" effects beyond the specific numbers of vehicles to be funded in the core DOE-awarded plan. [22, 23]

---

[21] Hydrogen Fuel Cell Partnership, *Cost Comparison and Fuel Technology Direction - Battery Electric Bus vs. Fuel Cell Bus*, July 2020, https://h2fcp.org/sites/default/files/07-24-2020-Foothill-ZEB-Update-to-Board.pdf

[22] California Air Resource Board, *Advanced Clean Fleets*, https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets/about

[23] UC Davis created a scenario in its recent hydrogen modeling report that is aligned with the ARCHES vision on FCEB and FCET stock growth to 2030 and beyond, but with "multipliers" that include uptake of significant numbers of LD vehicles and a range of smaller trucks and vans than may be in the direct ARCHES hub program. UC Davis Institute of Transportation Studies, *California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California: Final Synthesis Modeling Report*, April 2023, https://escholarship.org/uc/item/27m7g841

1.4. Expected Impact of Hydrogen in Transportation

Benefits to Justice40 Communities

The transportation sector accounts for most of the criteria pollutant emissions in California and Justice40 communities are the most heavily impacted. By eliminating these pollutants and the noise from conventional transit buses and trucks, zero-emission, quiet FCETs and FCEBs will significantly benefit communities. Economic benefits include opportunities for good-paying jobs building stations and service facilities, along with operating and maintaining FCEVs and fueling infrastructure. There will be jobs for those entering the workforce as well as up training opportunities so current workers can benefit economically during the energy transition. In the longer term, if advances in the MDHD FCEV market spur expansion of the LD FCEV market as projected, communities will also benefit from having zero-emission passenger vehicle options that do not require plugging in at home or work, which is often not feasible for low-income residents who may largely reside in multi-unit dwellings without dedicated garages or parking spaces where chargers can be installed.

Enables the larger hydrogen economy

Trucks and buses can be strong early adopters of hydrogen fuel at volume, which can spur relatively large-scale production and distribution systems for hydrogen and bring down the costs across the supply chain as envisioned by ARCHES.

Key to achieving state climate and clean air targets

FCEV technologies are essential to enabling California's zero-emission transportation and greenhouse gas reduction goals and are a cornerstone of the state's zero-emission vehicle (ZEV) policy. While California will need both battery electric vehicle (BEV) and FCEV options, FCEVs are the most promising one-to-one replacement for HD trucks and buses requiring long driving range, stringent duty cycles, heavy payloads, and fast refueling. FCEVs may also more easily serve locations like ports and airports where electric infrastructure for charging is not easily accommodated and provide resilient capabilities to operate fully during and after natural disasters. This will help ensure that zero-emission trucks and buses fully serve communities impacted by proximity to ports, warehouses, or heavy freight corridors, and/or wildfire and other disaster risk.

Essential complement to battery electric technology

Battery electric and hydrogen FCEVs each have distinct and complementary advantages and disadvantages, depending on the context in which they are deployed. For example, fuel cells can even be utilized for BEV charging deployment. Fuel cells may thrive in one use case, batteries in another. Pursuing both zero-emission solutions puts California in the best position to reach 100% zero-emission transportation.

1.5. Workforce Implications of Hydrogen in Transportation

Hydrogen fuel cell electric transportation will require jobs across the supply chain, including the design, manufacturing, assembly, maintenance, sales, and operations of vehicles, refueling stations, hydrogen production and liquefaction facilities, and delivery systems. Workforce training will be needed in a wide range of disciplines to prepare workers for the emerging hydrogen FCEV industry, enabling them to apply their talents to FCEVs and hydrogen refueling. Examples range from certification in safety standards to re-skilling workers accustomed to diesel vehicle and infrastructure construction, maintenance and operations. Skilled communicators will be needed for outreach to existing and potential new workers to raise awareness about the opportunities for near term jobs and long-term careers in the hydrogen transportation field, and trainers will be needed to lead the workforce development. It will be important to roll out training opportunities on a timeline that is coordinated with the roll out of hydrogen transportation technologies to ensure workers are available when required. Also critical will be apprentice opportunities that facilitate entry into the hydrogen transportation workforce.

Labor training centers, community colleges and workforce investment boards can play pivotal roles in preparing workers in relevant trades, while universities will be essential to educate the engineers, business leaders, and other highly skilled workers of a fully realized hydrogen fuel cell electric transportation industry. Technology suppliers and vehicle OEMs, in collaboration with educational institutions, can also play roles in developing the content for workforce training as they can provide the latest knowledge on the technology and make it relevant to the current state of the art. Corporations with existing networks and vehicle servicing centers can play a role in distributing relevant educational content. These entities can be instrumental in establishing apprenticeships that will be vital to developing the hydrogen transportation workforce. Additionally, standardized training and certification programs for firefighters, bus and truck drivers, and facility staff will foster a uniform and comprehensive approach to operating HD FCEVs and their supporting infrastructure, contributing to safer and more successful fleet operations.

1.6. Intersection of Transportation with Other Sectors

Intersection with Production, Distribution, and Storage

Growing hydrogen use for on-road transportation will require parallel growth in hydrogen production and distribution infrastructure. Hydrogen supply (100% renewable and low carbon intensity in the case of ARCHES projects) will need to be delivered to public and private refueling stations via truck at least through 2030, except in a few cases where pipelines may make sense given volumes and timely construction. However, by 2040, pipelines are expected to play an important role in delivering hydrogen to stations.

The ability of hydrogen to be produced and delivered at low cost will also greatly impact the economic case for FCETs and FCEBs, the market success of which will largely depend on the price of delivered hydrogen becoming cost competitive with diesel fuel. Many analysts project that hydrogen must be delivered at no more than $2-3/kg to achieve $6/kg at the pump (post-incentive), the estimated requirement to achieve cost competitiveness for HD FCEVs. Achieving the DOE's primary goal of reducing the cost of clean hydrogen production is therefore critical to enabling hydrogen transportation market maturity.

The hydrogen transportation market is exposed to potential investment and stranded asset risk in the absence of state-led analysis and policy planning to address potential technology conflicts. One example is the parallel development of compressed hydrogen and cryo-liquid supply chains. As the system evolves toward pipeline transmission, the market will need to decide whether to route hydrogen directly to stations for final compression, or to area terminals for liquefaction and final delivery by tanker truck.[24]

Intersection with Rail, Ports, and Aviation

Synergies with rail, ports and aviation sectors may arise via commonly used hydrogen storage and supply terminals, with trucks or pipelines providing "last mile" delivery services to refueling points for each type of end use.[25] Hydrogen use in port applications and aviation are covered in separate white papers.

---

[24] liquefaction is not likely to occur at stations, given the need for scale in this step

[25] Notably, there are several ongoing developments taking place in the California passenger rail sector that are likely to be significant in their impact on the design and operation of the ARCHES hydrogen hubs. Specific projects are:

- SBCTA Zero-Emission Multiple Unit (ZEMU) rail vehicle that will operate between San Bernardino and Redlands and should come into service in 2024, with four to twenty-five trainsets operational by 2027.
- Caltrans ZEMU rail vehicle fleet that is planned for operation on the Metrolinx commuter rail lines, such as Antelope Valley Line, which are mandated to come into service by 2035.

Hydrogen fuel cell electric rail technologies may share many co-benefits with the roll out of hydrogen storage and vehicle refueling infrastructure. Examples of opportunities are:

- Rail refueling locations could act as mini-hubs that can also be used by other hydrogen off-takers. Hydrogen could be produced on-site and transported by rail to meet the projected daily demand for the rail network and other users.
- Workforce transition planning is included as a core part of the hydrogen fuel cell rail (Hydrail) development. The scope of this work, which is likely to include the creation of training courses at community colleges, could become a starting point for broader training schemes that will be needed to support the roll out of FCETs and FCEBs.
- The rail sector could drive the technology development of new high-throughput hydrogen refueling systems, which will also be needed for FCETs, and support innovations in hydrogen supply and storage systems, such as the use of liquid hydrogen.
- Managing the safety risks of operating hydrogen fuel cell vehicles in tunnels is a core component of Hydrail's efforts, among other safety regulations, codes and standards, which could benefit on-road FCEVs.
- Caltrans will be developing communication and education strategies related to hydrogen transportation for its existing and potential rail customers, which can also benefit outreach to other stakeholders.
- Developing working relationships with first responders and municipalities to put in place appropriate emergency protocols to respond to rail incidents will foster confidence in responding to on-road vehicle and station incidents.

Daily demand for hydrogen to operate the current intercity services is on the order of 20 metric tons (22 tons), and if the increase in service frequency envisaged in the State Rail Plan occurs, this would increase to 40 metric tons per day.[26] Caltrans partner Valley Link also has similar consumption calculations based on the initial operating phase (22 miles from Dublin/Pleasanton to Mountain House) and is forecasting approximately 4 tons/day of hydrogen consumption by 2030 from four double trainsets (each trainset

- Caltrans Hydrail hydrogen locomotive fleet, mandated to come into service by 2035, is planned to operate on the three Intercity routes in California: San Joaquin, Pacific Surfliner, and the Capitol Corridor.
- Valley Link passenger rail system that will operate between Dublin, Pleasanton, and Lathrop and come into service in 2028.

[26] California Transportation Agency, *California State Rail Plan*, https://dot.ca.gov/programs/rail-and-mass-transportation/california-state-rail-plan

with two 4-car FLIRTS) operating peak periods and six single trainsets operating off peak periods. This number goes up to 8 tons/day by 2040 with the full build of Valley Link to North Lathrop where there would be ten double trainsets operating peak periods and ten single trainsets operating off peak periods.

Section 2: Challenges of Hydrogen in Transportation

2.1. Technical Challenges

The following are key challenges to adopting renewable clean hydrogen in the transportation system in California.

Achieving high station reliability to foster trust and a smooth-running system

Customers must have reliable stations to ensure they are satisfied with their FCEVs. Robust technical and performance standards, and the skilled workforce to implement them, are needed to ensure a successful station roll out. Each new station, and particularly larger stations, will have improved components making stations more reliable. Older stations need to maintain and upgrade their equipment to ensure reliability and safety. According to reports such as the 2023 Joint Agency Staff report on AB 8 LD station reliability has been impacted by hydrogen supply disruptions, which should be alleviated by greater quantities and diversity of production, distribution and storage. [27] Other lessons from LD stations are expected to be learned from the CEC's IMPROVE for H2 solicitation (GFO-23-64), which will fund projects that support hydrogen station reliability.[28] Another potentially useful tool is the hydrogen station prognostics health monitoring (H2S PHM) model developed to minimize unexpected downtime by predicting the remaining useful life for primary hydrogen station components within the major station subsystems.[29] Mobile hydrogen fueling can be deployed to help enable reliable fueling. A larger, more diverse market should drive competition that will improve operational strategies and commitment to ensuring station reliability.

[27] California Energy Commission, *Joint Agency Staff Report on Assembly Bill 8: 2023 Annual Assessment of the Hydrogen Refueling Network in California*, December 2023, https://www.energy.ca.gov/sites/default/files/2023-12/CEC-600-2023-069.pdf

[28] California Energy Commission, *GFO-23-604*, 2023. https://www.energy.ca.gov/solicitations/2023-11/gfo-23-604-improvements-maintenance-processes-reliable-operations-are

[29] International Journal on Hydrogen Energy, *Hydrogen station prognostics and health monitoring model*, January 2024, https://www.sciencedirect.com/science/article/pii/S0360319923040533

Uncertainty regarding how liquid and gaseous hydrogen will play out in the future

Over the next five to ten years, an important question will be whether the standard for hydrogen refueling for transportation will be gaseous, liquid, or a combination of the two. Liquid hydrogen carries advantages, such as better potential economics for truck delivery over long distances because a liquid tanker truck can hold a much larger mass of hydrogen (~4.5T LH_2) than a gaseous tube trailer (~1T GH_2). But this pathway also presents challenges, such as the potential for boil-off and high costs and losses associated with liquefaction. Liquid hydrogen is not yet used as fuel stored on board FCETs. However, cryopump dispensing into gaseous fuel storage on vehicles is gaining favor, permitting faster fueling than from gaseous hydrogen storage systems. The ARCHES TWG agrees that all gaseous and liquid hydrogen fueling options hold merit and should remain available as the market evolves.

Developing codes and standards that are adaptable to the future

As with many new technologies, codes and standards for MDHD FCEVs are in a nascent stage, even as these vehicles are starting to be deployed on the road.[30] Flexibility in these codes and standards will help avoid stranded assets. While there is a good deal of crossover between LD FCEVs and MD FCEVs that can inform code and standard development, HD FCEVs differ in important ways, such as using faster flow rates and different hardware.

Planning for hydrogen stations that serve multiple classes of FCEVs

Stations that serve MDHD FCEVs will be needed along freeway corridors, with MD FCETs also likely using neighborhood stations, and HD FCETs frequenting truck stops. Stations designed to serve LD, MD, and HD FCEVs present unique challenges, e.g. passenger car drivers won't wait in line with large trucks or use the same cardlock payment systems used to refuel trucks. However, different types of vehicles could be served in separate islands meeting unique performance requirements, such as fuel flow rate. Upcoming installations of such types of stations will inform the path forward.

Stations around port locations will need to serve drayage trucks as well as other trucks that travel to, but do not enter, ports. Together these types of stations can have major impacts on nearby Justice40 communities.

---

[30] Many new LD stations are using liquid hydrogen distribution and storage technologies with gaseous fueling dispensing at 70MPa (SAE J2601/1) and bus fueling with gaseous hydrogen at 35MPa (SAE J2601/2). A few HD stations will be using SAE TIR J2601/5 gaseous protocols in 2024 and these protocols will be implemented more widely in 2025. Liquid fueling protocols are being developed exclusively for heavy-duty fueling in ISO, and this standard will be available in 2026.

Determining hydrogen delivery truck specifications

Optimizing delivery of hydrogen to serve stations of various sizes and daily demand will require suitable hydrogen delivery truck and trailer sizes and specifications. Trucks used to deliver hydrogen are likely to run on hydrogen instead of diesel by the time a significant roll out of FCET hydrogen stations begins.

2.2. Market Challenges

Achieving FCET & FCEB Cost Competitiveness

FCEBs and FCETs must achieve cost-competitiveness with their diesel equivalents within the next few years and ultimately be equivalent to BEVs. TCO, including vehicle, fuel and operating costs, and non-cost factors like driving range, payload rating, reliability and durability, refueling time, and resiliency, must be comparable to other alternatives. FCEVs may hold significant advantages in some of these non-cost attributes compared to BEVs. However, it is difficult to accurately assess how much these advantages may offset the higher vehicle purchase and operating costs while enabling market growth.

California's clean truck, transit, and fleet regulations require a transition to ZEVs, which helps send a strong market signal to ensure some combination of battery electric and fuel cell electric options are adopted. Although ZEV sales required by the Advanced Clean Truck regulation and purchases by covered fleets required by the Advanced Clean Fleet regulation began in 2024, it will take time for the vehicle adoption numbers required in these rules to spur major market growth. Since these regulations are technology neutral, the regulations may not directly spur hydrogen FCEV market growth.

Skeptics sometimes argue that these rules and other market conditions do little to favor FCEVs and that BEVs are winning the market competition since there are many more models available for sale. Although FCEVs are entering the MDHD market more slowly than BEVs, their strong attributes indicate they could out-compete BEVs in some applications. While battery electric solutions for MD and short-haul trucks may become the most cost competitive ZEV option in the near term, the DOE projects that for long-haul HD trucks with greater than a 500-mile range, FCETs are anticipated to become the most cost-competitive option by 2035.[31] Our own analysis and communication with fleets suggests that, considering non-cost attributes and utility factors, FCETs will eventually be the preferred option for many fleets that need trucks traveling 200 miles

[31] U.S. Department of Energy, *Projects Zero-Emissions Medium- and Heavy-Duty Electric Trucks Will Be Cheaper than Diesel-Powered Trucks by 2035*, March 2022. https://www.energy.gov/articles/doe-projects-zero-emissions-medium-and-heavy-duty-electric-trucks-will-be-cheaper-diesel

or more each day. Many fleets may prefer FCETs in the near term, once the trucks and hydrogen are available at reasonable prices.

State of California incentive funds can be used to purchase vehicles in excess of those required for compliance with ZEV regulations (such as ZEV targets required by the Advanced Clean Fleet regulation). Fleets will need assistance navigating the intersection of regulatory requirements and funding sources to launch a successful FCET market. It is important to note that according to the HVIP FY 22-23 Implementation Manual, "HVIP will remain available to fleets purchasing a zero-emission truck or bus prior to compliance deadlines or in excess of regulatory requirements."[32] This means fleets may access incentives prior to regulatory compliance deadlines but not after. See Appendix B for more details on reducing vehicle TCO.

Reducing the Cost of Renewable Clean Hydrogen to Customers

For FCEVs to succeed, customers need reasonably priced hydrogen fuel. A general goal of ARCHES is to achieve a $5-6/kg refueling cost (outside of any taxes or subsidies) for hydrogen dispensed at 700 bar (10,000 psi) by 2030, to compete with diesel. While this price will be determined in part by hydrogen production and distribution costs, the costs of storing and dispensing hydrogen at refueling stations will also be critical. The price of hydrogen at the nozzle must be high enough for stations to earn a return on investment, after the cost of purchasing the hydrogen from distributors. The volume of fuel sold must also be great enough to generate the needed revenue to cover operating costs. See Appendix B for more details on reducing hydrogen costs to customers.

Achieving sufficient number and variety of FCEBs and FCETs models to fulfill needs of a wide range of fleets and to allow OEMs to reduce prices to competitive levels.

While the specific numbers of different models and production per model needed to satisfy the market need and reach full scale economies are uncertain, it is clear that some threshold will need to be reached for each major truck type, and in some cases for subcategories of trucks such as vocational trucks. The overall total market size for some vocational truck types might be too small on their own to spur economies of scale. Further research and on-going tracking can help identify where economies of scale for a larger truck sector can provide co-benefits to reduce costs in these smaller sectors. This could be part of a broader market tracking effort undertaken by ARCHES or other organizations.

---

[32] California HVIP, *Implementation Manual for the Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project,* August 2023, https://californiahvip.org/wp-content/uploads/2023/08/HVIP-FY22-23-Implementation-Manual.pdf

2.3. Policy Challenges

Policies are a fundamental driver of new energy market entrants, and FCEVs are no exception. Some key policy challenges facing the roll out of hydrogen transportation technologies in California and achieving scale include:

Navigating the intersection of regulatory requirements and funding sources to encourage initial adoption of FCEVs by fleets

California uses both regulatory requirements and incentive funding to move toward zero-emission transportation. These policies are complementary yet at times difficult for fleets to understand. ARCHES, along with resources such as Cal Fleet Advisor and state and local agency support, will need to assist fleets who aim to deploy HD FCEVs by identifying approaches that enable the use of incentive funds while also meeting fleet compliance requirements (e.g. under the Advanced Clean Fleets and Innovative Clean Transit regulations).[33]

Permitting timelines for refueling infrastructure

Like electric charging and other clean energy technologies, permitting timelines for hydrogen refueling risk slowing down the roll out of critical infrastructure needed to advance HD hydrogen transportation. SB 1418 (Archuleta, Chapter 607, Statutes of 2024) mirrors the streamlined permitting requirements for EV charging stations in AB 1236 (Chiu, Chapter 598, Statutes of 2015) and requires cities and counties to adopt a model ordinance and checklist of all requirements with which hydrogen fueling stations must comply with. This legislation builds upon the requirements set in SB 1291 (Archuleta, Chapter 373, Statues of 2022) which requires jurisdictions to streamline hydrogen station permitting provisions.

Enable station providers to survive the initial "valley of death"

Providing economic incentives, like the LCFS Hydrogen Refueling Infrastructure program and other measures to ensure station operators can continue to operate through the initial period when demand is ramping up will be critical to ensure long-term market success.

[33] Cal Fleet Advisor guides small fleets and owner-operators as they switch to zero-emissions vehicles. https://calfleetadvisor.org/

Meeting FCET targets in essential applications like drayage trucks that typically rely on a secondary market

The current lack of a secondary market or even established residual value for FCETs is a challenge that must be overcome to ensure the transition to zero-emissions trucks succeeds for all fleets, including small, less capitalized fleets that depend on lower cost, used vehicles. Large fleets typically replace their vehicles approximately every three to five years. California may need to find ways to more rapidly enable FCET adoption in applications dominated by small fleet operators, such as drayage trucks.

Ensuring even and equitable playing fields

A policy challenge for all emerging clean technologies is designing incentives, requirements and regulations in ways that consider how incumbent fossil fuel and earlier arriving clean technology market competitors have received direct and indirect support and seeking to ensure an even and equitable playing field for new market entrants. This will certainly be true for FCETs and FCEBs.

Integrating and harmonizing various California hydrogen transportation planning initiatives

As a global frontrunner in hydrogen transportation, California is home to several statewide and regional planning initiatives focused on rolling out hydrogen for the transportation sector and other markets. In addition to the ARCHES hub transportation effort, state initiatives announced or undertaken recently include:

- Governor Newsom's announcement that GO-Biz would be undertaking a Hydrogen Market Development Strategy as a complement to the state Zero-Emissions Vehicle Market Strategy.[34]
- CALSTART's Roadmap to Fuel Cell Truck Commercialization.[35]
- The CEC's award solicitation for creating Implementation of Medium- and Heavy-Duty Zero-Emission Vehicle Infrastructure Blueprints.[36]

---

[34] Office of Governor Gavin Newsom, *Governor Newsom Announces New Strategy to Develop a Hydrogen Economy of the Future*, August 2023. https://www.gov.ca.gov/2023/08/08/governor-newsom-announces-new-strategy-to-develop-a-hydrogen-economy-of-the-future/

[35] CALSTART, *Roadmap to Fuel Cell Electric Truck Commercialization*, 2024, https://calstart.org/roadmap-to-fcet-commercialization/

[36] California Energy Commission, *GFO-23-603*, https://www.energy.ca.gov/solicitations/2023-09/gfo-23-603-implementation-medium-and-heavy-duty-zero-emission-vehicle

- The CARB's 2022 Scoping Plan Update which additionally relies substantially on renewable clean hydrogen to meet California climate goals in the transportation sector.[37]

Making sure these various plans are aligned and send cohesive market signals will be important to successfully rolling out hydrogen in California's transportation market.

More details on opportunities, policy challenges and recommendations to overcome them are in Section 3.1. and Section 5.

2.4. Social Challenges

Developing community trust and acceptance

To realize the potential of FCEVs to benefit California communities, the fuel cell and hydrogen stakeholders developing and implementing projects need to earn the trust of those communities. Building trust and acceptance will depend on addressing common community concerns, including:

- *Safety* - That hydrogen will not increase risk of harmful explosions in communities
- *Environmental* - That using hydrogen will not perpetuate dependence on fossil fuels, impact local air quality, or contribute to climate change.
- *Nuisances* - Ensure that disruptions to their communities (e.g. with traffic, construction nuisances) will be minimized.

Responding to these concerns will entail continued outreach, collaboration and education, as well as consistent adoption of best practices, codes, and standards, along with early and visible successful deployments. Transit presents a strong opportunity, as FCEBs are already commercially available, and public fleets directly serve communities, offering riders and neighbors a chance to build familiarity through personal experience. Positive experiences of clean air, reliable service, good neighborliness, and safe operations can go a long way toward changing minds and building community acceptance.

Misunderstanding, misinformation and miscommunication among key messengers

Information about hydrogen and fuel cell electric vehicles is often either absent or inaccurate at community meetings. Educating journalists, community leaders, and other

[37] California Air Resources Board, *Scoping Plan for Achieving Carbon Neutrality*, November 2022, https://ww2.arb.ca.gov/sites/default/files/2022-12/2022-sp_1.pdf

important messengers with scientific facts will be key to counteracting misinformation. Developing positive experiences among drivers will also be critical, as happy drivers make good messengers.

Building acceptance and accelerating the pace of adoption among fleet managers

Fleets are going to be essential early adopters of FCEBs and FCETs. In fact, they will be required to adopt zero-emission vehicles incrementally over the coming years by California's Innovative Clean Transit Rule and Advanced Clean Fleet Rule, supported by various incentive programs. For hydrogen FCEV options to be attractive and adopted at scale, fleets will need conveniently located and reliable stations, excellent performance and reliable vehicles, and a positive user experience, all at a competitive price.

Section 3: Developing the Hydrogen and Transportation Market

3.1. Opportunities to Overcome the Challenges

To develop a self-sustaining hydrogen transportation market at scale, it is important to recognize and seize the following opportunities:

1. **FCEV technology will help trucks and buses reach fully zero-emission operation within California**, which likely will not happen with battery electric technology alone.[38] Significant progress is possible by 2030. As the 5th largest economy in the world and longtime launchpad for clean transportation innovation, California's leadership will likely have ripple effects nationwide and internationally.
2. **FCETs will help fleets preserve vital operations and meet critical needs**, such as driving range, payloads equivalent to diesel trucks, refueling time requirements, and maximum resiliency during periods of grid outages resulting from natural disasters.
3. **FCEBs have reached a mature state of technology readiness,** and transit agencies are recognizing that this technology can be cost competitive with the potential to replace conventional buses one-for-one without sacrificing performance and operational efficiencies.

[38] CALSTART, *Roadmap to Fuel Cell Electric Truck Commercialization*, March 2023, https://calstart.org/wp-content/uploads/2023/03/Roadmap-to-FCET-Commercialization.pdf

4. **Transportation and hydrogen jobs can be secured across the supply chain for skilled workers.** New and displaced workers can build the skills needed to build and maintain vehicles, fueling stations and the systems that support their operations.
5. **Matching diesel vehicles on TCO can happen relatively soon,** once renewable clean hydrogen cost targets are met and vehicle purchase costs begin to reach parity with conventional vehicles, as production and supply chain volumes expand. Incentives to bridge the gap to cost competitiveness will be essential to reach full commercialization and a self-sustaining market.
6. **A wide range of manufacturers are preparing to launch or have launched HD FCEV models, including at commercial scale,** particularly Class 7 and 8 HD trucks, such as the NorCAL ZERO Project and Nikola's commercially available FCETs. The largest bus manufacturer in the U.S. is already producing hundreds of FCEBs,[39][40] and the second largest bus manufacturer is planning to begin within the next few years.
7. **Replacing diesel trucks with zero-emission FCETs will dramatically cut criteria pollutant emissions in Justice40 communities,** reducing one of the major sources of negative health impacts among those most harmed by conventional diesel truck emissions. FCEBs can also significantly improve air quality and reduce noise in Justice40 communities.
8. **Providing hydrogen at traditional refueling centers that supply diesel today will help encourage FCEV adoption and accelerate the shift from diesel – one of the most polluting types of fossil fuels – to zero-emission fuel cell vehicles.** With supportive policies that help even the playing field, over the next 10-15 years renewable clean hydrogen can be expected to replace a large percentage of on road diesel fuel in California.
9. **MDHD FCEV market development will greatly expand demand for hydrogen production, efficient distribution, storage and supply, and refueling infrastructure.** This will stimulate growth in the LD FCEV market and accelerate station technology improvements across vehicle classes. Some HD refueling stations may be designed to also serve medium-duty vehicles and LD vehicles, expanding refueling options for all classes of vehicle. Notably, LD FCEVs can

---

[39] New Flyer. *New Flyer awarded largest hydrogen fuel cell-electric contract in company history, 108 buses to California's SamTrans.* October 2024. https://www.newflyer.com/2024/10/nfi-subsidiary-new-flyer-awarded-largest-hydrogen-fuel-cell-electric-contract-in-company-history-108-buses-to-californias-samtrans/

[40] Mass Transit Mag. *TTC contracts New Flyer for 186 Xcelsior CHARGE NG™ heavy-duty transit buses* 2023.https://www.masstransitmag.com/bus/vehicles/hybrid-hydrogen-electric-vehicles/press-release/53062551/new-flyer-ttc-contracts-new-flyer-for-186-xcelsior-charge-ngtm-heavy-duty-transit-buses

enable ZEV adoption among those who cannot easily charge at home, which tends to include lower-income, multi-unit family residents in dwellings without designated parking.

10. **Storage and distribution infrastructure investments, as well as applying knowledge gained through developing MDHD FCEVs, can be leveraged to decarbonize other transportation applications** such as rail, off-road heavy equipment (e.g. at ports and airports), aviation, and shipping.

3.2. Achieving Critical Mass

Hydrogen stakeholders across sectors must collaborate to launch the hydrogen vehicle industry and achieve critical mass, which entails achieving:

- Volume to reach economies of scale in relevant vehicle, station, and hydrogen distribution component manufacturing.
- Technology readiness level (TRL) 9 (proven in actual operating environment).
- Cost targets reached for competitive return on investment.
- Volume of truck manufacturing to drive the price down and reach ARCHES targets.
- Volume of hydrogen production to drive price at the pump down to $5-6/kg.
- Incentive funding for fleet owners so they can operate at a TCO comparable to diesel or natural gas.

Transit buses and fleets will be key to building up initial roll out and creating a pool of buyers that provides certainty for OEMs, as well as to relieve the pollution burden caused by freight and public buses that typically drive through and idle in Justice40 communities. While ARCHES is focused on transit and Class 8 FCETs for their potential to provide early benefits, other types of fleets and trucks can contribute to the larger picture of achieving scale in hydrogen ground transportation applications. Municipal, vocational and delivery fleets, along with rail and airport fleets, where hundreds of vehicles need to transition to zero-emission at locations with high electricity infrastructure constraints, should be examined as part of the state's hydrogen transportation strategy.

3.3. Working Together

Specific initiatives currently underway demonstrate opportunities for collaboration between fuel production companies, infrastructure developers, LD, MD, and HD FCEV manufacturers to build out a system in a concurrent and coordinated fashion.

As an example, in 2023 the NorCAL ZERO project began deploying what will be a total of 30 Class 8 FCETs, operating to and from the Port of Oakland. This project is a collaborative effort involving as many as 16 participating private companies and public agencies, providing fuel, fueling infrastructure, vehicles, service and maintenance support, and fleet services. The project requires capital and operating costs to be similar to operating a diesel truck fleet providing drayage and regional haul services. To meet that requirement, the project secured state and local subsidies resulting in a near TCO equivalency.

Section 4: Recommendations

The following are ten recommendations to help ensure development of a self-sustaining hydrogen transportation market in the freight and transit sectors in California, with specific collaborative actions that could support each one.

1. Enable FCEBs and FCETs to become competitive with diesel vehicles in the next few years.

Operators of FCEBs and FCETs must realize an economically viable return on investment, which will depend on relative vehicle and fuel prices and operating costs, available incentives, and non-cost factors like driving range, payload rating, reliability and durability, refueling time, and resiliency. Advantages in the non-cost areas should allow FCEVs to compete at a somewhat higher TCO than BEVs. Today, some fleet operators are willing to purchase a FCET over a battery electric truck because those fleets need to make fewer operational adjustments with a FCET compared to a battery electric truck. “De-risking” purchases and leases by fleets will be a critical component of creating a successful market. Smaller fleets may need extra assistance because they have less access to capital and often purchase used vehicles.

COLLABORATIVE ACTIONS

A. **Secure transparent, long-term, and consistent funding for fleet operators that is sufficient to bridge the upfront capital and ongoing operational cost gap** between HD FCEVs and diesel heavy-duty HD vehicles during the early market stage.

B. **Make it easier for end users to access funding** and plan a transition to FCEVs.

C. **Ensure incentives and programs that support ZEV adoption and infrastructure enable all ZEV options**.

D. **Continue to emphasize that battery electric and fuel cell electric transportation technologies are complementary**, and both are needed to achieve state ZEV goals.

E. **Create subsidized FCET leasing programs to help reduce upfront costs and financing hurdles.** Programs like the Truck Loan Assistance Program would align with SB 372 (2022) and its mandate to create a MDHD Zero-Emission Vehicle Fleet Purchasing Assistance Program.

F. **Target incentives where they can accelerate FCET adoption fastest and where funds can be best leveraged.** Large-scale deployments with large fleets will increase volume production early on and set the stage for less costly and more affordable second-hand FCETs in later years, enabling broader adoption.

G. **Establish bulk purchases of "standardized" FCEBs through ARCHES and state contracts.** This may reduce costs by assuring manufacturers of larger production volumes and enabling them to secure better supply chain pricing.

H. **To improve early market adoption, a program could be developed to guarantee a residual value of the FCET.** This would remove a write-down risk for the large shipper or carrier who initially purchases the new vehicle, as well as provide the state access to secondary market vehicles that could be resold by dealers to smaller fleets and independent operators who would benefit from the lower price tag of a used FCET.

I. **Additional early vehicle and infrastructure funding incentives would assist transit agencies,** who provide a critical public service that especially benefits Justice40 communities.

J. **Address the challenge of road weight limits for zero emission trucks.** Fully loaded FCETs can exceed the weight allowed on some California roads, thus decreasing the cargo capacity and revenue generation potential compared to diesel trucks, which weigh less**.** This will require action at the California Department of Transportation and other agencies.

K. **Continue to leverage regional funding programs like the Carl Moyer program** to support early adoption of HD FCEVs and fueling stations.

2. Achieve an acceptable retail hydrogen price "at the nozzle" of $5-6/kg or less.[41]

The retail hydrogen price should compete with other fuels, considering the fuel efficiency advantage in certain duty cycles of HD FCEVs over diesel, recognizing that this will vary by vehicle type and use patterns. Utility advantages and operational efficiencies of FCEVs may mean the fuel cost does not have to match the per-mile fuel cost of BEVs, but the TCO needs to be competitive. This will also benefit from incentives for some years but must eventually be true without any incentives.

COLLABORATIVE ACTIONS

A. **Build transparency, longevity, consistency and adaptability into hydrogen production pricing incentive programs to encourage the sustained investment** so FCEVs can reach TCO competitiveness with diesel. For programs (e.g. LCFS, IRA) to succeed in incentivizing clean fuels, including renewable clean hydrogen, pricing must be sufficient to level the playing field over the long term, and predictable to encourage continuous investment. Pricing mechanisms must be flexible to respond to market dynamics, avoid incentive-induced price inflation, and ramp down as the market matures.

B. **Align goals and plans for vehicles, stations, renewable clean hydrogen supply, and hydrogen cost/price for 2031.** The SB 643 report could be a mechanism for establishing this plan, in connection with the Governor's proposed Hydrogen Market Development Strategy.

C. **Promote development and utilization of hydrogen fuel cell technologies in other sectors** (e.g. rail, cargo-handling equipment, power) to increase hydrogen demand and help achieve economies of scale.

D. **When calculating carbon intensity of hydrogen fuel, credit low carbon process energy along with renewable feedstocks.** Process energy for compression, refrigeration, liquefaction, pumping, and distribution is significantly higher for hydrogen than for other fuel options.

E. **Assist fleets in accessing sufficient subsidies to procure affordable hydrogen supply in the early stages of deployment**, to help overcome the "valley of death" that challenges all emerging technologies when competing in established markets.

---

[41] U.S. Department of Energy, *2022 Clean Hydrogen Strategy and Roadmap*, June 2023, https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap

3. Build enough stations, including public refueling stations, to support heavy-duty vehicles operating "over the road."

FCETs will need to refuel at public stations and must have a sufficient, reliable network to operate in their service territory, throughout the state and interstate. California needs to plan for 50 or more stations by 2030, with a substantial number operating in the next two years. Station placement should maximize utilization while ensuring drivers do not have to deviate more than a few minutes from their planned routes to fuel.

COLLABORATIVE ACTIONS

A. **Complete infrastructure roadmaps and implement the plans and recommendations without delay.** Work with state agencies, ARCHES, and groups like the California Transportation Commission SB 671 Working Group to implement a station and associated infrastructure roll-out plan.

B. **Streamline the station planning and construction process to dramatically reduce the timeline from site selection to construction and operation of stations.** For example, expedite power connections for new HD refueling stations, which to date have been hampered by delays and high costs. Likewise create an energization tariff to enable utilities to connect service lines from the distribution grid to the station instead of requiring facilities to do so, typically and substantially higher cost. And allow alternative energization solutions where existing infrastructure is insufficient to meet the energy demand for fleet applications.

C. **Continue to leverage state funding, such as the Energy Infrastructure Incentives for Zero-Emission (EnergIIZE) Commercial Vehicles, with federal funding available through the Infrastructure Investment and Jobs Act (IIJA) Alternative Fuels Corridor Funding** to advance hydrogen station development in California.

D. **Consider supporting modular refueling as a bridge technology** to encourage early adoption of heavy-duty FCEVs while fixed stations are being built.

E. **Work with the CPUC and utilities to create programs that enable hydrogen refueling stations to benefit the grid.** Hydrogen stations have the potential to be good grid citizens with programs that incentivize refueling when it is best for the grid. This option cannot be realized at existing facilities that add hydrogen stations because, unlike electric charging stations, there is no energization tariff available for hydrogen stations, and therefore no separate meter permitted that can track the station's energy usage. Creating an energization tariff for hydrogen stations would unlock the full potential of these stations to provide grid benefits.

F. **Continue hydrogen station incentives for both capital and operating costs** to ensure that stations will remain operational until sufficient hydrogen demand is achieved, enabling long-term self-sufficiency.

G. **Build on the success of the Hydrogen Refueling Infrastructure credits for LD stations and apply the same credits to stations that serve MDHD FCEVs** to compensate investors for the financial risk of station ownership.

H. **Work with the U.S. Environmental Protection Agency to adopt Renewable Identification Number credits for hydrogen to establish a level-playing field with compressed natural gas (CNG) fuel.**

4. Reduce the capital and operating costs for public transit agencies to achieve parity with diesel and CNG costs.

FCEBs are demonstrating excellent performance with the ability to serve well over 90% of public transit routes. New models available in 2025 will provide additional fuel storage to enable extended ranges of 350 miles or more. The main challenges are the capital cost of buses and the price of fuel. About 80-90% of transit agency capital costs are covered by the federal government, but until the overall federal allocations are increased, the cost gap between FCEBs and conventional internal combustion engine buses will require additional funds.

COLLABORATIVE ACTIONS

A. **Provide capital incentives for early adopters until production and supply volumes achieve economies of scale** that results in vehicle price parity. Transit agencies require deficit funding, and to afford the high capital cost of FCEBs they will need continuing subsidies over the next several years.

B. **Negotiate lower prices based on group purchases on behalf of multiple agencies within California and in collaboration with other regions nationally.**

C. **Standardize FCEB specifications in conjunction with bulk purchases to help reduce manufacturing costs.**

D. **Incentivize new fueling infrastructure and retrofit of existing maintenance facilities to safely work on FCEBs**. The cost of a hydrogen fueling station to serve 100 or more buses ranges between $8 and $10 million, considerably less than the infrastructure needed to recharge a similar number of battery electric buses. Transit agencies need financial assistance to build out this infrastructure.

5. Earn the trust and acceptance of communities in which the emerging hydrogen FCET and FCEB technologies are deployed.

Conventional trucks and buses are among the leading causes of pollution in Justice40 communities. However, some do not yet trust hydrogen fuel cell electric technologies.

COLLABORATIVE ACTIONS

A. **Support continued development of safety codes and standards that ensure safe operation of FCEVs and refueling infrastructure.**

B. **Develop and deliver community outreach and education programs to build knowledge and dispel misinformation** regarding FCETs, FCEBs, and hydrogen infrastructure.

C. **Empower, and where necessary, fund community stakeholders to participate in decision making** regarding the roll out of FCETs, FCEBs and hydrogen infrastructure, including supporting ARCHES' community benefits engagement efforts.

D. **Prioritize workforce training for community members where FCETs and FCEBs are deployed.**

E. **Support rapid and successful deployment of FCEBs** as these vehicles can be the early community ambassadors of hydrogen and fuel cell technologies.

6. Support a sufficient number and variety of FCEB and FCET models to fulfill the needs of a wide range of fleets and to incentivize OEMs to reduce prices to competitive levels.

Models must be available in a range of truck classes and equipped to handle different driving duty cycles and payload requirements. The top priority categories are for short-haul ("day truck") drayage and regional-haul operations, which are typically handled with Class 8, container-carrying tractors. Other high priorities include Class 7 urban/day and box trucks, Class 4-6 delivery trucks, and HD pickup trucks.

Zero-emission long-haul interstate trucks and intercity passenger coaches (three-axle buses) will require fuel cells to meet range and sustained speed requirements. Prototype vehicles and pilot deployments are needed to demonstrate performance in advance of commercialization.

COLLABORATIVE ACTIONS

A. **Incentivize deployment of at least 5,000 Class 8 FCETs and 1,000 FCEBs** by offering funding to cover the incremental costs.

B. **Promote an "ecosystem" approach to deploying FCETs by clustering deployments of 100 to 500 trucks in corridors** to support a competitive TCO, with incentives, during the initial stages of deployment**.** This will require a collaborative planning and deployment effort in which fleet operators, truck OEMs, truck maintenance and repair services, fueling station vendors, and fuel providers work together to synchronize the timing of the rollout of vehicles and infrastructure.

C. **Ensure that vehicle OEMs are guaranteed a sufficient volume of production** to realize economies of scale and a robust supply chain.

D. **Identify additional early compliance funding to support Class 4-6, Class 7, and potentially smaller trucks** depending on where FCEVs appear to be a good fit.

E. **Research market potential and develop prototype fuel cell electric coaches** for intercity service and demonstrate in pilot deployments.

F. **Reduce or eliminate sales tax for zero-emission trucks and buses**, including a national exemption of the 12% Federal Excise Tax on trucks.

7. Align the rollout of all aspects of the hydrogen system, so that sufficient hydrogen fuel is available to meet growing demand, and infrastructure is available to transport, store, and dispense this fuel.

Station availability and hydrogen supply must lead to truck and bus growth, so vehicles never face a shortage of supply or lack locations in key areas to refuel.

COLLABORATIVE ACTIONS

A. **Work with the U.S. government and other states to ensure compatibility between California systems and those of other states,** as well as a continuous system of supply and retail availability of hydrogen fuel on highway systems for trucks (and cars) beyond California's borders.

B. **Develop technical standards for heavy-duty fast fueling** in the timeline needed to support rapid roll out.

C. **Create a fuel supply exchange, possibly managed by ARCHES, to match producers with incentives** and to enable fleet operators and station providers to obtain the lowest price possible for their fuel.

8. Ensure hydrogen refueling station technologies and systems are widely compatible with vehicles and that station overall and hourly dispensing capacities (rates, numbers of refueling positions, etc.) are sufficient to handle average and peak demands, in a rapidly growing system.

Hydrogen stations must provide sufficient fuel in a timely manner so trucks and buses can operate freely over their typical routes. Some excess capacity will be needed in early years to ensure peak demands are met, and station operators will need financial support until the system becomes fully sustainable. Technologies to support both liquid and gaseous fueling systems must be commercially available and reliable, and must be assessed to determine the most efficient, economical and feasible options that ensure compatibility across the system.

COLLABORATIVE ACTIONS

A. **Anticipate vehicle growth, as well as needed station growth and capacities,** and work with station developers who understand the needs of truck drivers to plan station locations and capacities.

B. **Carry out periodic tracking and performance evaluations** to help ensure reliability of stations funded by the state.

C. **Do not be overly prescriptive regarding what types of vehicles can be served at stations**. Ensure that stations and vehicle onboard storage systems are designed to be compatible with one another.

D. **Provide federal and state funding for public transit agencies** to build non-public fueling stations at their operating divisions.

E. **Assess the risks and benefits of liquid versus gaseous hydrogen station storage and dispensing to vehicles** to fully understand the tradeoffs, compatibility issues, and optimal and most feasible pathways for achieving the supply, station capacity, refueling requirements, costs and system expansion speeds needed to reach scale.

9. Similar to EVSE, ensure vehicle roll out is accompanied by refueling station ubiquity with high reliability to achieve successful market development.

COLLABORATIVE ACTIONS

A. **Support workforce training** to ensure abundant skilled technicians are available to successfully address reliability issues.

B. **Upgrade outdated stations to state-of-the-art technology.**

C. **Consider utilizing a predictive model, such as the hydrogen station prognostics health monitoring (H2S PHM),** to assess the remaining useful life for station components.[42]

D. **Apply relevant lessons learned from the CEC's IMPROVE for H_2 solicitation (GFO-23-604),** which aims to fund projects that improve hydrogen station reliability in California.[43]

10. Expand workforce training to ensure that FCEVs and stations are built in the timeframe and standards necessary to achieve a robust hydrogen transportation market.

Across the supply chain, from vehicle manufacturers and maintenance facilities to refueling station developers and operators, trained technicians will be needed to troubleshoot and maintain complex systems. These resources are in short supply today. Current workers may not be informed about FCEVs and hydrogen and may worry this is not a viable career path. They also may identify with their jobs in the conventional vehicle industry and resist the changes inherent in the transition to ZEVs.

POLICY ACTIONS

A. **Implement a strong outreach program** to inform existing and potential workers of the employment opportunities related to hydrogen transportation.

B. **Build on programs such as the CEC's IDEAL ZEV Workforce Pilot Project (GFO-21-602) to fund workforce development and training programs** aimed at creating a skilled workforce capable of implementing ZEV transportation, including FCEVs, and hydrogen refueling station maintenance at commercial scale.

C. **Support and fund expanded workforce training programs at public transit agencies,** who have established training programs for their staff.

D. **Develop a vocational training program through the California community college system in collaboration with organized labor unions** including re-skill training for experienced automotive workers and apprenticeships that enable new entrants to join the labor force.

---

[42] International Journal of Hydrogen Energy, *Hydrogen station prognostics and health monitoring model*, January 2024, https://www.sciencedirect.com/science/article/pii/S0360319923040533

[43] California Energy Commission, *GFO-23-604*, https://www.energy.ca.gov/solicitations/2023-11/gfo-23-604-improvements-maintenance-processes-reliable-operations-are

E. **Support high level skills training at state universities** to support the emerging hydrogen transportation system.

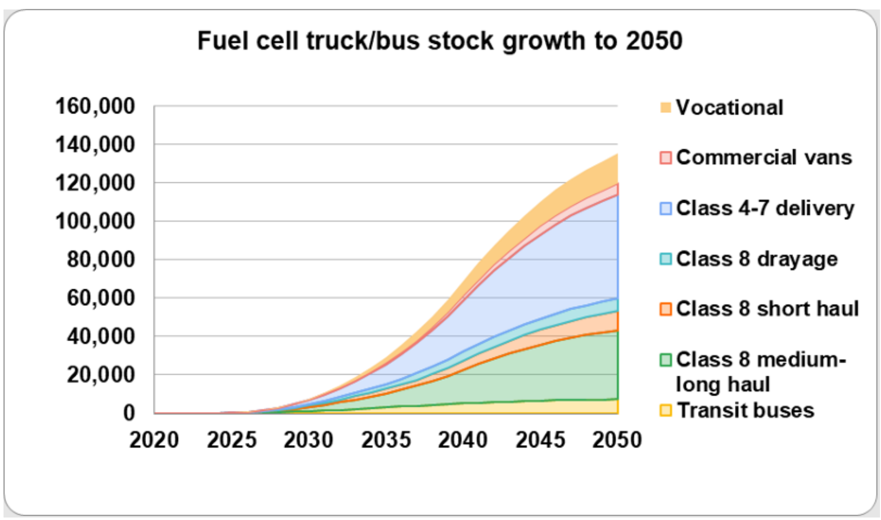
F. **Broaden the outreach of educational programs by including hydrogen fuel cell curricula in middle and high schools.**

Appendix A: Projections for Market Growth

UC Davis created a scenario in its recent hydrogen modeling report that is aligned with the ARCHES vision on FCEB and FCET stock growth to 2030 and beyond, but with "multipliers" that include uptake of significant numbers of LD vehicles and a range of smaller trucks and vans.[44] In this scenario, HD FCETs reach about 5,000 vehicles by 2030, and FCEBs as well as MD FCETs each reach about 1,000 vehicles. Rapid growth is projected after 2030, resulting in a total vehicle stock of about 140,000 by 2050 (Figure 1). In comparison, CARB's 2022 Scoping Plan is more optimistic, with over 15,000 FCETs by 2030 and nearly 300,000 by 2045.

LD FCEVs have a very wide range of potential market uptake, but even very low percentages would result in large numbers of vehicles and hydrogen demand by 2030 and beyond. CARB's 2022 Scoping Plan projections anticipate 130,000 LD FCEVs on the road in California by 2030, 350,000 by 2035, and nearly 800,000 by 2045.[45] In the UC Davis scenario shown in Figure 1 below, LD FCEV stock projections are somewhat lower, reaching 150,000 by 2030 and then, at a constant 5% market share, 500,000 in 2035 and 1.3 million by 2045 (out of 35 million LD vehicles of all types by that year).

Figure 1. Scenario for potential fuel cell truck and bus vehicle stock growth over time



Source: UC Davis Institute of Transportation Studies[46]

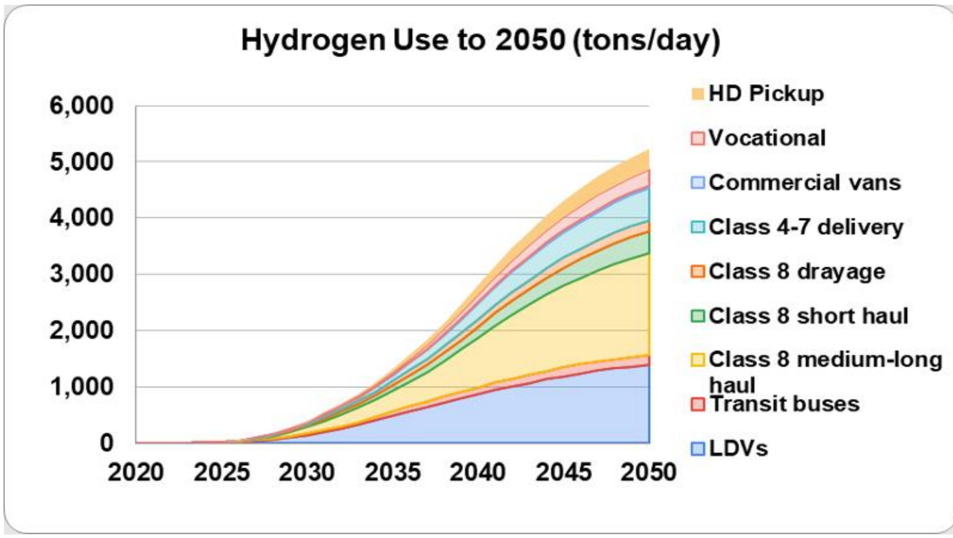
[44] UC Davis Institute of Transportation Studies, *California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California: Final Synthesis Modeling Report*, April 2023, https://escholarship.org/uc/item/27m7g841

[45] California Air Resources Board, Scoping Plan for Achieving Carbon Neutrality, 2022, https://ww2.arb.ca.gov/resources/documents/2022-scoping-plan-documents

[46] UC Davis Institute of Transportation Studies, *California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California: Final Synthesis Modeling Report*, April 2023, https://escholarship.org/uc/item/27m7g841

Even with these projections on FCEV stocks that are low compared to CARB's, hydrogen demand growth is dramatic, reaching about 500 tons/day by 2030 across all vehicle types, and over 5,000 tons/day by 2050 (Figure 2). Trucks and buses play a critical role in building demand, providing about 60% of the hydrogen demand in 2030 and 65% by 2050. Even without the LD vehicle-based hydrogen demand, the trucks and buses would require hundreds of tons per day of hydrogen by 2030, which should be sufficient to drive commercial hydrogen production and distribution systems.

Figure 2. Resulting hydrogen use by vehicle type to 2050 in scenario



Source: UC Davis Institute of Transportation Studies[47]

[47] UC Davis Institute of Transportation Studies, *California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California: Final Synthesis Modeling Report*, April 2023, https://escholarship.org/uc/item/27m7g841

Appendix B: Vehicle and Fuel Cost Considerations

Vehicle purchase and fuel cost incentives can have large financial and market creation impacts, spurring a virtuous cycle of accelerated early adoption and economies of scale in vehicle production, system, and station infrastructure. This in turn drives down cost and improves the operating environment, thus spurring more demand. Financial incentives may need to be in place for many years to reach the point at which private capital earns a return on investment and becomes economically sustainable. However, the overall cost of such support would likely be small compared to the eventual size of the system being created and the benefits it will offer.

In the current incentive landscape in California, the HVIP program offers $240,000 for a new HD FCET. Small private fleets are eligible for a 15% plus-up and small public and nonprofit fleets with 20 or fewer MDHD vehicles are eligible for an additional 100% plus up. Larger private fleets with over 101-500 vehicles receive a minus 20% voucher adjustments from the base amount of $240,000 while fleets with more than 500 vehicles receive a -50% adjustment. Thus, the incentive amount varies depending on the vehicle purchaser's fleet size. Although the voucher amount is considerable, it may not offset higher purchase costs and is limited by the exclusion of vehicles used for compliance with state zero-emission mandates.

As the market grows and production volumes increase, vehicle costs and prices should drop. There is a wide expectation that FCET costs will soon be lower than for battery electric trucks, at least for long-haul applications. Eventually, FCETs are expected to reach parity with diesel trucks, but the vehicle sales volumes and exact dates to achieve these milestones are unclear.

As a rough example, if HD (Class 7 & 8) trucks currently had a purchase price that averages $300,000 more than diesel equivalents, and this cost difference were to decline 20% with each 1,000 trucks sold in California, reaching $0 when 5,000 trucks are sold, this would represent an overall total additional cost of $750 million. This could cover the period to 2030, per the UC Davis scenario above. Considering other types of FCETs, the overall additional purchase costs over this period could be over $1 billion. If 50% of this cost is covered by incentives, they would represent at least $500 million over six years.

In addition to the purchase cost of vehicles, operational costs also contribute significantly to the future cost-competitiveness of FCEVs. Among the most significant of these operational expenses is the cost of fuel, which is discussed below. Other ongoing cost challenges related to FCET and FCEB early market status will also need to be overcome, such as the high cost of insuring vehicles while their purchase price remains relatively high.

The price of hydrogen at the pump will depend in large part on the price of hydrogen production, which is addressed in a separate ARCHES white paper. Here we draw on information in available recent reports and the DOE's U.S. National Clean Hydrogen Strategy and Roadmap to focus on transportation related hydrogen costs after production, including:

- costs to transport hydrogen to stations
- costs to store hydrogen at terminals or stations
- station-related costs to operate and dispense hydrogen to vehicles
- costs of vehicles

With a linked target for hydrogen production costs of $1-2/kg, this leaves about $4-5/kg cost for all subsequent steps to the point of refueling. The following section focuses on achieving this target.

Current Hydrogen Costs

While it is not easy to isolate the actual costs of hydrogen along each step of its supply chain, overall cost estimates are available. According to the DOE, the current average retail price of hydrogen fuel for transportation ranges from $13 to $16 per kilogram in the United States, which mostly occurs in California where all but one commercial hydrogen station in the nation is located.[48] In some recent cases, the hydrogen price at the pump (nozzle) has reached $30+ per kg. These costs relate to a) small station sizes with high operating costs, along with various maintenance and down-time related costs, and b) lack of hydrogen availability, with shortages increasing prices. High cost of hydrogen transportation and storage also contribute to costs at the pump rising over $12/kg.

Public transit agencies are paying between $8 and $10 per kilogram of delivered liquid hydrogen. An additional $1 per kilogram is expended to further compress and dispense the fuel into buses. While this is considerably less costly than the retail price, it still amounts to more than double the cost per mile for FCEBs compared to diesel and CNG buses. These prices do not include amortization of capital costs, since transit infrastructure depends on federal, state, and local subsidies. These short-term prices,

---

[48] U.S. Department of Energy, *National Clean Hydrogen Strategy and Roadmap*, September 2022, https://www.hydrogen.energy.gov/docs/hydrogenprogramlibraries/pdfs/clean-hydrogen-strategy-roadmap.pdf?Status=Master

including recent spikes, are expected to drop fairly dramatically as a) new hydrogen supplies are created, such as low-cost solar electricity-based electrolysis farms, and b) more large-scale provision of hydrogen is created, such as the use of up to four-ton liquid hydrogen delivery trucks.

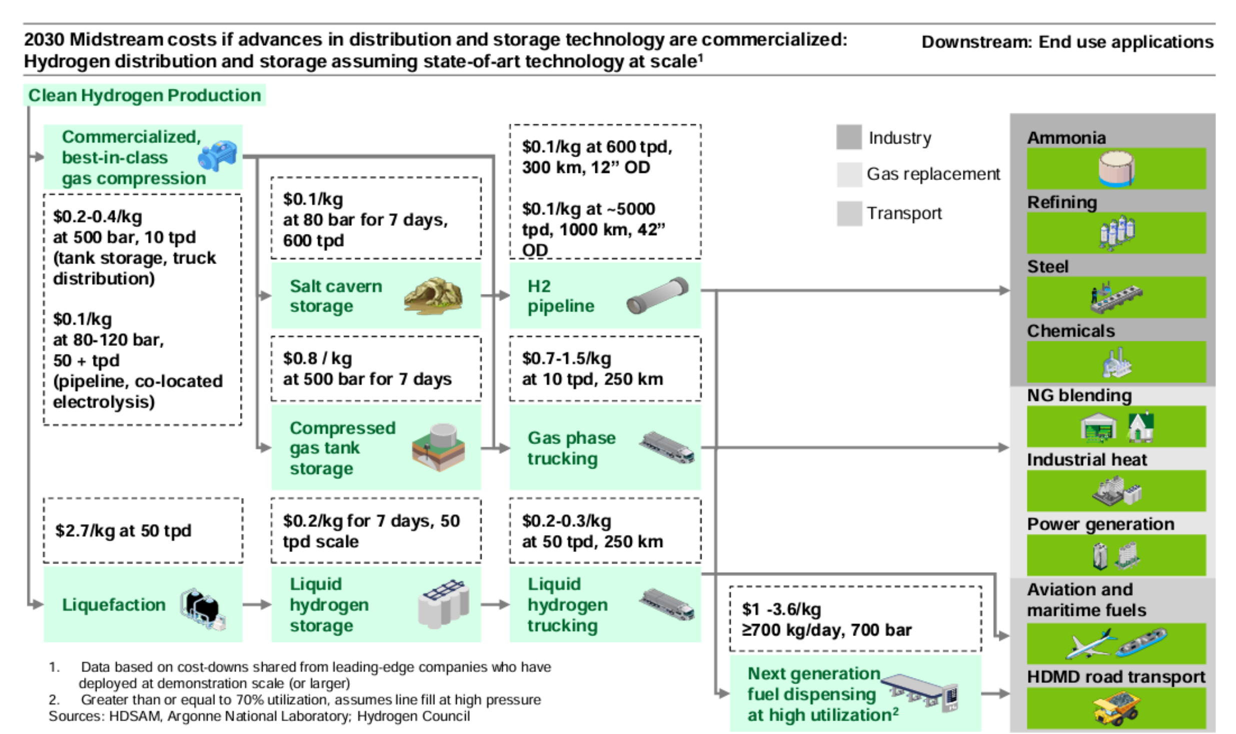
As is true for vehicles, station costs may be high during early phases but should come down as more stations are rolled out and perhaps especially as station sizes increase enabling scale. Both scale and optimization can contribute to substantial cost reductions in stations, and thus station-related hydrogen costs, but station operators must survive a period with high incoming hydrogen prices and a small number of customers (i.e. low daily volume sales) for that hydrogen.

While today's LD vehicle refueling stations typically have capacities of 500-1,500 kg/day (0.5 to 1.5 metric tons), stations designed to serve trucks are likely to be much larger. This is because trucks may refuel with 40-50 kg each time compared to LD vehicles, which may only take around 3-4 kg. If 100 trucks each refuel at an average of 40 kg/day, then there must be a total capacity of 4,000 kg/day (4 metric tons) per to adequately serve the trucks' refueling needs. Such larger capacities may help reduce the per-unit cost of components but will make stations more expensive to construct than today's smaller stations. Larger capacities also result in more pressure on the system to quickly increase demand to help create the market that will pay for these investments.

The previously mentioned DOE U.S. National Clean Hydrogen Strategy and Roadmap report contains the figure below (Figure 3) that shows their estimated ranges of cost for four stages of the hydrogen supply chain: compression/liquefaction (column 1), storage (column 2), transport (column 3) and station costs (column 4). For the first three stages, the table indicates the combined costs could range from $1.60 to $2.40 per kg for gaseous systems with gaseous truck delivery, and $2.90 to $3.10 for liquid systems. Station costs are shown with a wide range of $1.00 to $3.60 per kg, depending on station size and technology. Note that the figure does not include hydrogen production costs, which could add several dollars more to the overall cost, though DOE targets $2/kg by 2026.

While the specific costs of stations constructed in California and how these costs may differ by technology and over time are difficult to predict, it appears likely that larger stations will certainly achieve significant cost reductions per unit. It also appears that stations using liquid systems will be lower cost than those with gaseous systems due to less expensive equipment and energy costs.

Figure 3. DOE Roadmap Report projections in 2030 midstream costs of clean hydrogen for transportation



Source: DOE[49]

The DOE cost range for delivery, storage, and stations is consistent with findings using hydrogen supply chain and cost models, such as Argonne National Lab's HDSAM and HDRSAM, to estimate costs for truck-oriented stations and supply systems. UC Davis recently created cost estimates as presented in Fulton et al, 2023.[50] The conclusion is that with relatively short (less than 200 mile) transportation distances and use of liquid tanker trucks to larger stations, delivery and station costs below $3 should be possible. Combining this with $2 production cost would achieve the $5/kg overall cost target.

A key aspect to building larger, higher capacity stations is the system used to transport hydrogen to these stations and storing that hydrogen at the stations. A system using 400 kg gaseous storage delivery trailers would require ten deliveries per day to support 4 tons/day of demand; this approach will be expensive and cumbersome. An alternative

[49] U.S. Department of Energy, *2022 Clean Hydrogen Roadmap and Strategy*, June 2023; Figure 25 from report, repurposed from DOE's report Pathways to Commercial Liftoff: Clean Hydrogen, https://www.hydrogen.energy.gov/library/roadmaps-vision/clean-hydrogen-strategy-roadmap

[50] UC Davis Institute of Transportation Studies, *California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California: Final Synthesis Modeling Report*, April 2023, https://escholarship.org/uc/item/27m7g841

using liquid hydrogen tanker trucks at 4,000 kg (4 tons) per shipment, as is currently available, will be far more practical and less expensive, and may become a common practice for HD vehicle stations. However, this means that stations would be handling and dispensing liquid hydrogen rather than gaseous, which is an important technology choice. This is a new technology, while there are approximately a dozen stations serving passenger FCEVs that utilize liquid hydrogen delivery, there are basically no stations in operation today at the 4 ton/day level needed for HD service using liquid hydrogen.

These types of stations could have important advantages over gaseous storage and fueling station systems. One is that they can be fitted with fast fill refueling systems, allowing HD FCETs to refuel in 15 minutes or less, without any delay between vehicles for the system to "recharge." A second is that these stations can easily be scalable to increase to 8 tons/day, if they take two shipments of hydrogen from 4-ton tanker trucks (as long as their dispensing systems are also sized to that capacity). Reaching 8 tons/day may be sufficiently large for highway stations to fully serve large numbers of trucks, as long as there are stations every 50 to 100 miles along a highway system. The specifics of station sizing and location, along with growth factors as the numbers of trucks increases, need further planning.

One question is whether such a station can recover its capital and operating costs in early years, and another is the number of truck customers per day (and hydrogen sales) that would be needed to achieve this. While a detailed analysis of station economics is outside the scope of this paper, it is reasonable to expect reaching this point will take some years. For example, if 6,000 trucks were running on California's highways by 2030, and 60 truck refueling stations were in operation around the state by then, and these trucks refueled an average of 30 kg/day, then a total of 180 tons/day of hydrogen demand would be generated, to be met by the 60 stations. This would be an average of 3 tons/day each. This level of demand should be sufficient to create a financially viable situation for station operators as well as fuel providers, that should only continue to improve as the system continues to grow.

However, in the early days of this scenario, if only 600 trucks were running on the road, then only 1/10 of the 2030 demand would be in place, generating only 1/10 the fuel demand and related revenues. Even if there were far fewer stations the average revenues per station may be too low to achieve cost recovery. Rolling out stations early is very important, but low numbers of trucks will make the station economics quite challenging in the beginning without financial support.

Adding to the challenge, there is a minimum number of stations needed to create a viable state-level system. The CTC and the SB 671 Workgroup[51] estimated that the minimum number of HD fueling stations to cover major highway routes within the state is around twenty. Having 500 trucks refueling at 20 stations, however, is likely financially unviable for station owners. Therefore, growth towards higher truck adoption must be rapid to reach the 5,000 truck and 50 stations by 2030 target set by UC Davis[52].

If the 5,000-truck target is achieved by 2030, and station and truck numbers increase steadily between 2024 and 2030, then stations might generate half the revenues overall over six years, compared to what is needed to cover costs. This suggests a subsidy of 50% might be needed for stations to survive until they reach a point of financial sustainability. If an average cost of station construction were $3 million/ton/day of capacity (UC Davis estimate) and needs to be subsidized at 50%, then $300 million in subsidies would be required for the $600 million needed to build 200 tons/day station capacity statewide. This could be in the form of percentage co-funding for the first 50 stations, possibly as a declining cost share each year, or with a certain year cutoff date, to encourage rapid station construction and eventually phase out this subsidy.

The state of California has notably been at the forefront of offering ZEV infrastructure incentives, with the most recent CEC 2022-2023 Investment Plan including $2.9 billion[53] in ZEV infrastructure incentives. However, whether these programs will be sufficient to help launch a self-sustaining hydrogen transportation market and how they will coordinate in terms of amount and timing with federal programs, including the DOE hydrogen hub program, will need further examination. Starting in 2013 with the passage of AB 8, 20% of ZEV infrastructure funding was carved out for hydrogen stations (as opposed to electric charging), and as of September 2023 with the passage of AB 126, the carve out for hydrogen will be reduced to 15%.[54][55] The state LCFS also includes a Hydrogen Refueling Infrastructure capacity credit to help support the buildout of passenger vehicle stations, which CARB is considering extending to stations that serve medium- and heavy-duty vehicles. What is certain is that as with any major energy transformation, sustained public investment for a period will be imperative to realizing success.

---

[51] California Transportation Commission, *SB 671 Clean Freight Corridor Efficiency Assessment, September 2023, https://catc.ca.gov/-/media/ctc-media/documents/programs/sb671/092523-sb671-draft-assessment-a11y.pdf*

[52] UC Davis Institute of Transportation Studies, https://escholarship.org/uc/item/133538gw

[53] California Energy Commission, *2022–2023 Investment Plan Update for the Clean Transportation Program*, https://www.energy.ca.gov/publications/2022/2022-2023-investment-plan-update-clean-transportation-program-0

[54] *AB 8*, September 2013, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=201320140AB8

[55] *AB 126*, October 2023, https://leginfo.legislature.ca.gov/faces/billNavClient.xhtml?bill_id=202320240AB126

Appendix C: ARCHES Transportation Working Group Participants

Scott Brandt, University of California Office of the President

Grace Curtis, GO-Biz

Tyson Eckerle, GO-Biz

Angelina Galiteva, Renewables 100 Policy Institute

Michael Kashuba, GO-Biz

Angela Shepard, GO-Biz

Gia Vacin, GO-Biz

Michael Kashuba, GO-Biz

Yousif Abudra, Chevron

Tri Dev Acharya, California Air Resources Board

Andres Aguirre, Heliogen

Jordan Ahern, Strategen

Neal Aronson, San Luis Renewables, LLC

Mike Ashton, Linde

Lily Backer, Green Hydrogen Coalition

Benjamin Beaver, Siemens Energy, Inc.

Jackson Becce, NovoHydrogen

Serj Berelson, Mainspring Energy

Rob Best, Arup

Dhruv Bhatnagar, Strategen Consulting

Mahesh Biradar, General Motors

Justin Bracci, National Renewable Energy Laboratory

Michelle Browne, EnviroGen Technologies

Dennis Burke, City of Long Beach

Emily Burks, AES

PJ Callahan, CTE

Joe Cappello, Iwatani

Shawn Carr, Strategen Consulting

Jack Chang, California Public Utilities Commission

Kristina Chavez Wyatt, San Benito County Business Council

Peter Chen, California Energy Commission

Janna Chernetz, AMOGY, Inc

Yachun Chow, California Air Resources Board

Abel Chuang, University of California, Merced

Mark Chung, National Renewable Energy Laboratory

Greg Cogut, AltaSea

Matt Condara, Shell

Nicholas Connell, Green Hydrogen Coalition

Teresa Cooke, CA Hydrogen Coalition

Jim Corboy, Calvert Advisors, LLC

Shiloh Costello, Sacramento Municipal Utility District

William Crampton, H2APAC

Bart E. Croes, California Energy Commission

Ed Cubero, Amogy

Ash Dalal, EPRI

TaMarco Davis, Lone Cypress Energy

Mary-Rose (Szoka) de Valladares, ATOME Plc

Michael Debortoli, Northern California Power Authority

Robert Del Core, SYMBIO North America Corp

Maryam Delavarrafiee, California Air Resources Board

Kim Domptail, GHD Inc.

Ryan Doyle, GHD Inc.

Barron Effenberger, Caltrol

Fokion Egolfopoulos, University of Southern California

Matthew Elke, University of California, Berkeley

David Elpers, Nikola Corporation

Bill Elrick, Hydrogen Fuel Cell Partnership

Faye Farahmand, STV Incorporated

Hope Fasching, Green Hydrogen Coalition

Julie Felipe, City of Riverside

Maggie Field, Clean Air Task Force

Mark Filimonov, Momentum

Matthew Forrest, Daimler Truck North America

Michael Galvin, Port of Los Angeles

Monterey Gardiner, National Renewable Energy Laboratory

Philippe Gerretsen, Nikola Corporation

Michael Ginsberg, Avina Clean Hydrogen Inc.

Jacob Goldberg, Port of Los Angeles

Leslie Goodbody, California Air Resources Board

Matt Gregori, SoCalGas RD&D

Erica Grignaschi, Clearway Energy Group

Wilson Hago, Hago Energetics

Irfan Haider, Hyundai Motor Company

Jennifer Hamilton, CA Fuel Cell Partnership

Jennifer Hamilton, California Hydrogen Business Council

Michelle Han, Edison International

Kevin Harris, John Cockerill

Edwin Harte, SoCalGas

Preston Hayes, Electus Energy

Kim Henry, SPEC Services, Inc.

Natalie Hilburg, Heliogen

Njomele Hong, Acumen Transit

Mack Hopen, Modern Electron

Randy Howard, Northern California Power Authority

Martin Howell, Arup

Taylor Huff, H Cycle

Alex Ivanenko, HyWatts Inc

Matt Jackson, Crowley

Varalakshmi (Lakshmi) Jayaram, Ramboll US Consulting

Elizabeth John, California Energy Commission

James Kast, Iwatani Corporation of America

Jay Keller, Zero Carbon Energy Solutions

Adam King, General Motors

Steve Kiser, WSP

Amy Kitson, SoCalGas

Michael Kleist, Sierra Energy

Tom Knox, Valley Clean Air Now

Cato Koole, Rocky Mountain Institute

Brian Krzycki, Worley

Krystyna Kubran, 352 Innovation

Ahmet Kusoglu, Berkeley Lab

Michael Lee, Symbio North America

Tracy Leslie, EPRI

Paul Lin, Southern California Gas Company

Tim Lipman, University of California, Berkeley TSRC

Jeffrey Lockett, Air Products and Chemicals, Inc.

Joseph Anthony Lopat, South Coast Air Quality Management District

Ehsan Madadi, California State University, Long Beach

Smaranda Marinescu, University of Southern California

Sam Markolf, University of California, Merced

Pierre Martin, Innergex Renewables Inc

Andrew Martinez, California Air Resources Board

Kristi McKenney, Port of Oakland

Kevin McNulty, Dynamis Energy, LLC

Darius Mehta, Garrett Motion

Brent C. Melot, University of Southern California

Adam Merah, Nel Hydrogen Corp.

Alexus Merino, City of Lancaster

Luke Miner, Jacobs

Matt Miyasato, FirstElement Fuel

Tom Mourmouras, Shell

Kelly Murillo, City of Riverside

Arnaud Namer, Universal Hydrogen

Jimmy O'Dea, California Department of Transportation

Peter Ogundele, GNA

Chuck Okolie, Amazon

Tomas Ortiz, California Energy Commission

Rebecca Pancheri, Look, Inc.

Aparajit Pandey, Rocky Mountain Institute

Krishna Patel, Clearway Energy Group

Dan Patry, AES Clean Energy

Victoria Pena, Sacramento Air Quality Management District

Lori Pepper, California State Transportation Agency

Grayson Perry, Woodside Energy

Mike Petouhoff, Arup

Giles Pettifor, Oxnard Harbor District - Port of Hueneme

Erika Pham, Mote

Alexander Piper, Rocky Mountain Institute

Raef Porter, Sacramento Metropolitan Air District

Pete Pugnale, FASTECH (Fueling and Services Technologies Inc.)

Deveny Pula, NECA LA

Steve Racoosin, Eco Energy International

Salim Rahemtulla, PowerTap Hydrogen Fueling Corp

Jeffrey Reed, University of California, Irvine

Anthony Reyes, Michelin

Wil Ridder, Tri-Valley - San Joaquin Valley Regional Rail Authority

Tomi Riley, Air Products

Cole Roberts, Arup

Katerina Robinson, California Energy Commission

Norman Rogers, USW Local 675

Nermina Rucic-O'Neill, Los Angeles Department of Water and Power

James Sagil, California State University Fullerton

Muhammad Sahimi, University of Southern California

Seema Santhakumar, Baker Hughes

Tim Sasseen, Ballard Power Systems

Tracy Sato, City of Riverside

Elizabeth Savage, AES

Chiara Scaramuzzino, Momentum

Michael Schmitz, ReCarbon

Jesse Schneider, ZEV Station

Kevin Shannahan, Robert Bosch LLC

Shaama Mallikarjun Sharada, University of Southern California

Mark Sheldon, Sheldon Research and Consulting

Cory Shumaker, Hyzon Motors USA

Matt Shumway, Mainspring Energy

Michael Simon, RockeTruck, Inc.

Devang Singh, ReNew Power

Scott Stewart Singletary, thyssenkrupp nucera USA

Mikhael Skvarla, California Hydrogen Coalition

Mikael Sloth, Nel Hydrogen

Todd Solomon, ZeroA

Siari Sosa, Southern California Gas

Varun Sree, Intersect Power

Charlie Stockton, EnviroGen Technologies

Joe Sullivan, NECA LA

Ian Sutherland, Jacobs Engineering

Roger J. Swenson, Clean Development International

Janice T. Lin, Green Hydrogen Coalition

Terry Tamminen, AltaSea

Alan Tan, Next Hydrogen Corp.

Shams Tanvir, California State University, Long Beach

Oleksiy Tatarenko, Rocky Mountain Institute

Bryan Taylor, Blackcurrant Inc

Akshay Thakur, Blackcurrant Inc

JuliAnne Thomas, Raven SR

Matt Thorington, Robert Bosch LLC

Valentino Tiangco, Sacramento Municipal Utility District

Sean Tiedgen, Shasta Regional Transportation Agency

Lindsey Tollefson, Jacobs Engineering

Mark Tollefson, Cal STA

Shailesh Topiwala, Robert Bosch LLC

Dietmar Trees, HyWatts Inc

Theo Tsotsis, University of Southern California

Peter Tuschinski, Siemens Mobility

Monique Valdez, FuelCell Energy

Sriram Varadarajan, Accenture

Vishnu Vijayakumar, Hyundai America Tech Center

Thomas Walker, Clean Air Task Force

Jack Walter, Valta Energy

Kirk Waltz, American Bureau of Shipping

Shannon Noll, General Motors

Scott Weaver, Ramboll US Consulting

Adam Weber, Berkeley National Lab

Michael Wheeler, Intersect Power LLC

Carson Wilcox, Sierra Energy

Paul Wilkins, Electric Hydrogen

Peter Willette, Momentum

Denita Willoughby, Avantus

Keith Wipke, National Renewable Energy Laboratory

Molly Yang, Hgen

Bill Zobel, Pilot

David Zurmuhl, Amog