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Fuel-Cell Vehicle and Hydrogen Transitions in California: Scenarios, Cost Analysis, and Workforce Implications

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RESEARCH REPORT

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CALIFORNIA

Fuel-Cell Vehicle and Hydrogen Transitions in California: Scenarios, Cost Analysis, and Workforce Implications

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16. Abstract
To achieve California's ambitious climate goals, a shift to hydrogen fuel for some transportation sectors may be essential. In this report, we explore the build-out of a hydrogen fuel distribution system including uptake of light-, medium-, and heavy-duty fuel cell electric vehicles. Our analysis of Base and High Case scenarios includes costs of building and operating a hydrogen vehicle and fuel system and estimates workforce impacts. We consider scenarios with about 125,000 vehicles by 2030 in the Base Case and 250,000 in the high case. This increases by an order of magnitude to 2045. Vehicle and station investment costs associated with the Base Case reach anywhere from $4 to 12 billion USD by 2030 and increase by a factor of eight by 2045. Costs per kg of hydrogen, including fuel transmission to stations and station costs delivered to vehicles, could be in the range of $4 to 8 per kg. This becomes $6 to 10/kg as a final delivered cost, if production of hydrogen were to cost $2/kg. Workforce impacts in the Base Case include 600 to 2,200 jobs created by 2030, rising rapidly thereafter. This report was prepared by the ITS-UC Davis Energy Futures Hydrogen Program in partnership with the UCLA Luskin Center for Innovation.

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The California Resilient and Innovative Mobility Initiative

The California Resilient and Innovative Mobility Initiative (RIMI) serves as a living laboratory – bringing together university experts from across the four UC ITS campuses, policymakers, public agencies, industry stakeholders, and community leaders – to inform the state transportation system's immediate COVID-19 response and recovery needs, while establishing a long-term vision and pathway for directing innovative mobility to develop sustainable and resilient transportation in California. RIMI is organized around three core research pillars: Carbon Neutral Transportation, Emerging Transportation Technology, and Public Transit and Shared Mobility. Equity and high-road jobs serve as cross-cutting themes that are integrated across the three pillars.

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Abbreviations and Acronyms

ARCHES	Alliance for Renewable Clean Energy Hydrogen Energy Systems
BEV	battery electric vehicle
CARB	California Air Resources Board
CCS	carbon capture and storage
CCUS	carbon capture, utilization, and storage
CO_2	carbon dioxide
CSTDM	California Statewide Travel Demand Model
CEC	California Energy Commission
EIA	US Energy Information Administration
EV	electric vehicle
FCEB	fuel cell electric bus
FCET	fuel cell electric truck
FCEV	fuel cell electric vehicle
FTE	full-time equivalent jobs
GH_2	gaseous hydrogen
GOOD	Grid Optimized Operation and Dispatch model (UC Davis)
H_2	hydrogen
HDV	heavy-duty vehicle
ICE	internal combustion engine
LCFS	Low-carbon Fuel Standard
LDV	light-duty vehicle
LH_2	liquid hydrogen
LMDV	light and medium duty vehicles
MDV	medium-duty vehicle
MHDV	medium and heavy-duty vehicles
PEM	proton exchange membrane (fuel cell)
PHEV	plug-in hybrid electric vehicle

RIMI	Resilient and Innovative Mobility Initiative
RNG	renewable natural gas
RPS	Regional Portfolio Standards
SMR	steam methane reforming
STIEVE	Spatial Transportation Infrastructure, Energy, Vehicle and Emissions model (UC Davis)
TAZ	transportation analysis zone (spatial disaggregation to transportation and land use-type areas)
TCO	total cost of ownership
WECC	Western Electricity Coordinating Council
ZEV	zero emission vehicle

Executive Summary

Executive Summary

As California and other areas of the US develop hydrogen hubs, their cost and workforce impacts have become critical concerns. This report presents UC Davis Hydrogen Program's Base and High Case scenarios for potential future uptake of light-, medium-, and heavy-duty fuel cell electric vehicles (FCEVs), and a supporting hydrogen system in California. These scenarios build on other recent UCD reports (ITS-Davis, 2024), particularly Fulton et al (2023). Related impacts on jobs are also evaluated.

Here, we present our results as follows:

1) Review of our hydrogen scenarios (Base and High Case)
2) Vehicle-related costs
3) Hydrogen station-related costs
4) Hydrogen delivery-related costs
5) Total, levelized hydrogen transported and delivered to vehicles
6) Workforce and job implications of developing a hydrogen system

Under this Resilient and Innovative Mobility Initiative (RIMI)-funded project, the UC Davis Energy Futures program has analyzed costs (items 1 and 2 above), while UCLA Luskin Center for Innovation has analyzed workforce and jobs implications. The same scenarios are used throughout the document, with UCLA using the UC Davis Base and High Case projections of vehicle sales, stocks, and fuel use for their workforce analysis.

Fuel-Cell Electric Vehicle Growth and Hydrogen Use Scenarios

The following summarizes our analysis and results for scenarios, costs, and workforce implications. Our Base Case scenario has been calibrated to be ambitious yet incremental. For trucks and buses, the Base Case aligns closely with California Alliance for Renewable Clean Energy Hydrogen Energy Systems (ARCHES) targets for 2030, with steady growth thereafter. Our High Case is more ambitious, assuming robust light-duty vehicle (LDV) and medium-heavy-duty vehicle (MHDV) markets along with rapid growth in refueling and hydrogen production capacities throughout the state. These are scenarios, not forecasts or predictions. They provide a structure for analyzing costs, required infrastructure, and other aspects of a commercial hydrogen fuel roll-out. More details about these scenarios are provided in our previous modeling report (Fulton et al, 2023).

Our Base Case and High Case scenarios project the numbers of fuel-cell vehicles in operation by vehicle type out to 2045, with 2030 serving as a milestone year (Figure ES-1). We assume that this stock of vehicles travels a certain distance per day and uses a certain amount of hydrogen per day. By 2045, the majority of these fuel-cell vehicles are LDV, even though they represent a very small share of zero-emission LDV sales: about 5% in 2030 and 12% in 2045. The remainer of sales are battery electric or plug-in hybrid vehicles. FCEVs attain their highest sales shares with heavy-duty vehicles (HDVs), and these have the largest demand for hydrogen. Medium-duty vehicles (MDV) also become important sources of demand by 2045. The proportions of FCEV sales across the different vehicle types are very similar in the Base and High Cases. The High Case generally has 2 to 2.5 times more FCEVs than the Base Case in both 2030 and 2045.

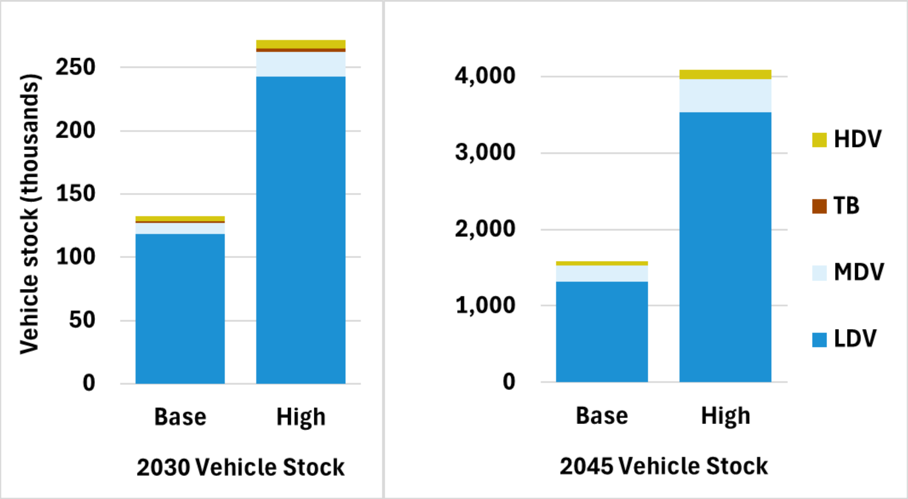

Figure ES - 1. Base and High Scenario projections of FCEV stock by vehicle type in 2030 and 2045.

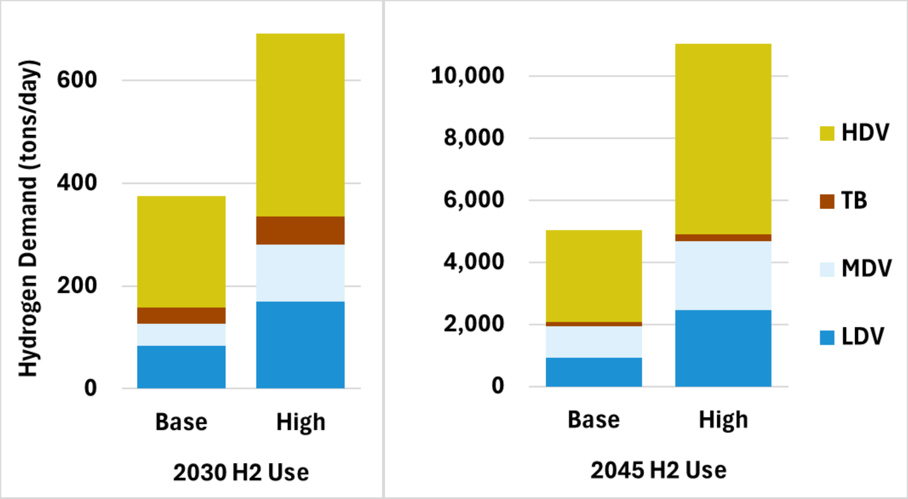

Figure ES - 2. Base and High Scenario projections of and hydrogen use by vehicle type in 2030 and 2045.

Hydrogen use associated with this stock of vehicles in 2030 and 2045 is commensurate with FCEV stock (Figure ES-2). As is true for vehicle stocks, hydrogen use grows significantly to 2030 then dramatically to 2050, reaching 5,000 tons/day in the Base Case and 11,000 in the high case. This represents close to four million tons per year in 2045, twice the current amount of hydrogen used by refineries in California, which dominate hydrogen use today.

The projected vehicle costs and associated hydrogen system costs, as well as workforce impacts, are all strongly linked to the number of vehicles and use of hydrogen fuel.

Cost Analysis Summary

For our cost analysis, the foregoing projection of sales and stocks of FCEVs, medium- and heavy-duty fuel cell electric trucks (FCETs), and fuel cell electric buses (FCEBs) was used to estimate fuel consumption, fueling station requirements, and resulting costs. We focus on costs of moving hydrogen from production/storage facilities to refueling stations and the costs of operating those stations. We consider both investment and per-kilogram levelized costs of these activities. We do not directly consider the costs of producing and storing hydrogen in any detail. We do include costs of either liquefaction or compression of hydrogen in preparation for transporting it, storing it at stations, and refueling vehicles. We also consider the possible total price of hydrogen at the pump by assuming potential production/storage costs, to estimate a final retail price.

We assume refueling stations use gaseous hydrogen (GH2) systems for light and medium duty vehicles (LMDV) and liquid hydrogen (LH2) for HDV stations, to derive approximate investment and per-kg costs each year, particularly by 2030 and 2045. Delivery and refueling are also important components of cost estimates included here because they are key aspects of the overall cost of hydrogen delivered to vehicles. These costs are additional to the remaining costs of hydrogen production and storage prior to delivery, which are not considered here except in a simplified manner.

Average distances between production locations and stations are assumed to be modest, consistent with current hydrogen production and station locations in California. Transmitting hydrogen via pipeline is not considered, in part because generating enough demand and building pipelines will take many years, while truck delivery can be implemented quickly for relatively small systems. Our main objectives are to clarify factors determining investment and levelized cost and to provide estimates for total investments needed to build out hydrogen systems out to 2045. We also estimate levelized hydrogen costs associated with building and operating this system.

The cost of purchasing vehicles (exclusive of government taxes or subsidies), when considered as an investment by users, dominates upfront hydrogen system investment costs (Figure ES-3), assuming a hydrogen transportation system demand for the Base Case target, equal to 400 tons/day by 2030 and over ten times that by 2045. However, if vehicle purchase costs of FCEVs are compared to equivalent gasoline or diesel vehicles, then this vehicle investment cost drops dramatically in the near-term. It becomes negative soon after 2030 for LDVs and by 2035 for medium- and heavy-duty vehicles (MHDVs). This reflects an assumption based on our prior studies and a range of other studies that FCEVs will eventually be cheaper to build and purchase than gasoline or diesel vehicles. This outcome depends on economies of scale and learning, i.e., strong growth in the market for these vehicles over time. Costs in the High Case reflect nearly two and a half times as many LDVs sold, and three times as many MHDVs sold—and thus hydrogen sold—as in the Base Case, in both 2030 and 2045. The investment per-unit cost estimates are accordingly lower in the High Case than Base Case, though much higher overall given the numbers of vehicles sold.

Apart from the purchase of vehicles, refueling station construction will incur substantial investment costs. Delivery by truck will not incur such a high investment cost but will require high operational costs. In our Base Case, the cumulative hydrogen transportation system investment costs, which include LDV and MHDV deployment and refueling infrastructure requirements, reach about $12 billion USD through 2030 and rise to about $80 billion through 2045. However, when considering only the incremental (i.e. additional costs) of new fuel cell vehicles (over the costs of gasoline or diesel vehicles), along with the *full costs* of new stations and delivery systems, the cumulative investment costs decrease dramatically to under $4 billion by 2030 and around $12 billion through 2045. We do not consider incremental costs for stations since these do not directly replace any other purchases. Our results show that when considering only incremental vehicle costs to 2030, less than half of the investment costs for LDVs are for vehicles; most are for stations. In contrast, more than half of investment costs for MHDVs are related to acquiring the vehicles. To 2045, incremental vehicle costs for all vehicle types drop to near-zero over the entire period; the only net investment costs are for stations.

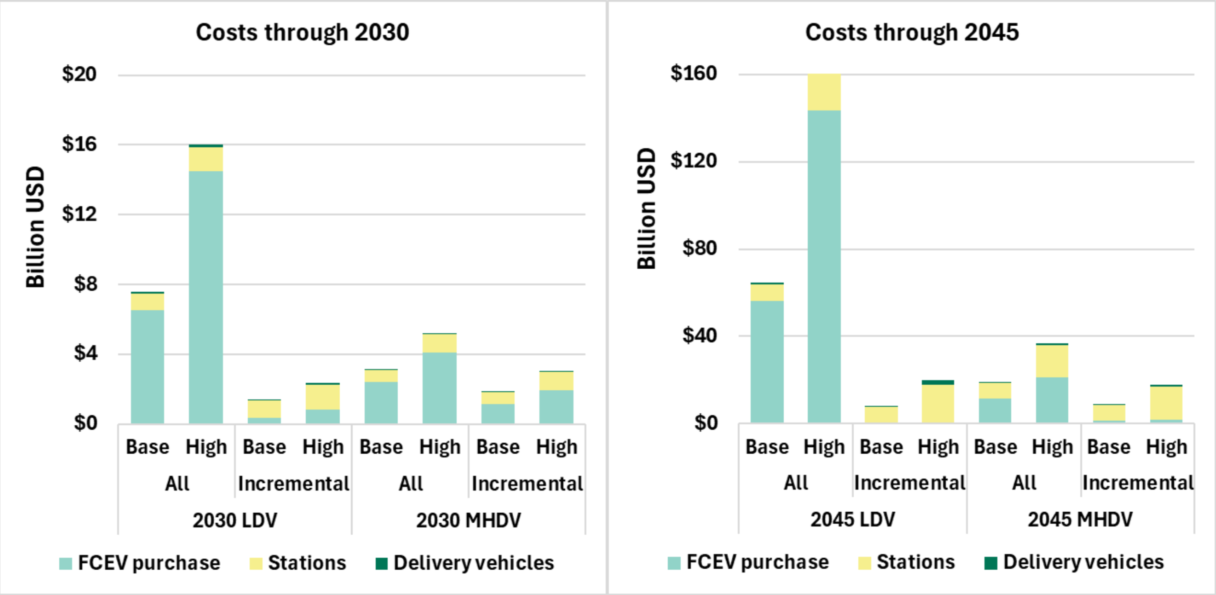

Figure ES - 3. Cumulative investment costs from 2023 to 2030 and 2023 to 2045 for LDVs and MHDVs; total and incremental.

Results for levelized costs of hydrogen delivery to fueling stations that serve LMDVs and/or HDVs (station costs) are summarized in Figure ES-3 for Base and High Cases. MDVs are included with LDVs, not HDVs, as they will typically use LMDV station systems. Key assumptions were made for the 2030 and 2045 cases and two LDV and HDV system types and are detailed in Table ES 1. These costs do not include production and storage of hydrogen before distributing it to stations by truck.

Table ES - 1. Factors and assumptions affecting costs for LMDV and HDV stations in 2030 and 2045. Assumptions are explained in the body of the paper.

	LMDV stations				**HDV stations**			
	2030		**2045**		**2030**		**2045**	
	Base	**High**	**Base**	**High**	**Base**	**High**	**Base**	**High**
Station capital cost per 1,000 kg/day capacity ($ millions)	3.6	3.6	2.8	2.8	2.3	2.3	1.8	1.8
Average station capacity (kg/day)	1,300	1,400	2,100	2,600	4,600	4,800	8,700	9,200
Hydrogen sales per day per station (kg)	700	1,200	1,700	2,100	3,700	3,800	7,000	7,400
Average utilization rate (percentage of station daily capacity)	56%	80%	80%	80%	80%	80%	80%	80%
Truck/trailer delivery capacity (kg)	800	800	1,000	1,000	4,000	4,000	4,000	4,000
Truck/trailer deliveries per day per station	0.9	1.4	1.7	2.1	0.9	1.0	1.7	1.8

In 2030, the cost of distributing hydrogen to stations, along with station costs of refueling vehicles in the Base Case, is about $7/kg for LMDV stations and under $4/kg for HDV stations (Figure ES-4). In the High Case, costs are much lower for LMDV stations at about $4/kg and are essentially unchanged for HDV stations. For LMDV stations, this is because building 175 stations by 2030 requires that these stations are severely underutilized for a few years while vehicles are few and hydrogen demand is low, driving up per-unit costs. This relationship is less pronounced for trucks, and for both LDVs and trucks in the High Case, given more vehicles per station leading to more station utilization by 2030. Cost and profitability challenges to LMDV stations in our Base Case could be substantial. However, the challenges are eliminated by 2033 as the number of vehicles becomes commensurate with the number of stations.

The delivery costs via compressed gas “tube trailers” for LMDV stations are considerably more expensive than via liquid tanker trucks for HDV stations, though they are not a large share of the overall picture (Figure ES-4). Station and delivery cost estimates do not include the costs of fuel production, compression, liquefaction, or storage before distribution. These “upstream” costs are outside the scope of this paper.

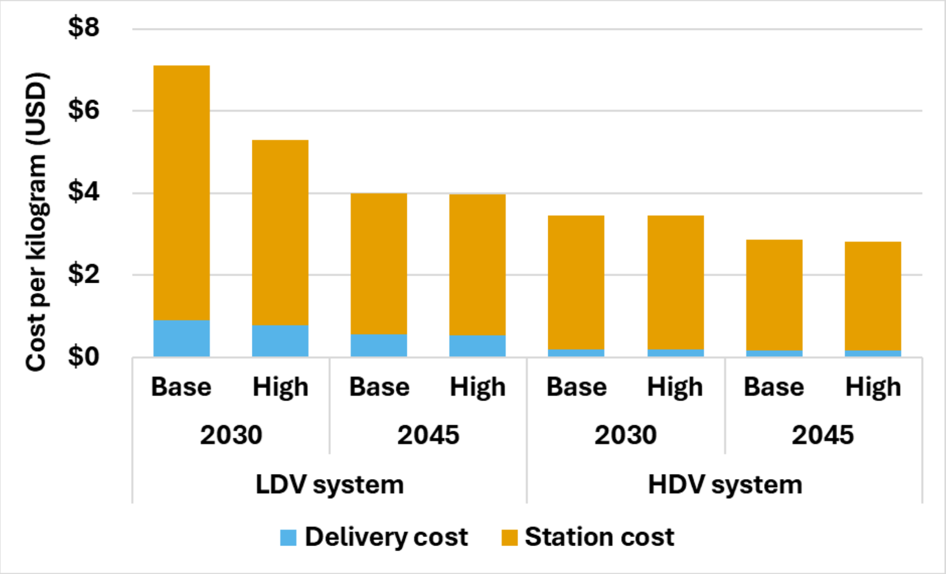

Figure ES - 4. Levelized costs of H_2 distribution and station refueling, USD/kg.

The cost advantage of HDV stations over LMDV stations reflects several advantages of HDV stations in this context: (1) their much larger average size, (2) higher utilization rates, as a percentage of capacity, in 2030 (mainly in the Base Case), and (3) use of liquid on-site storage and dispensing systems. On-site systems provide, in addition to high refueling speeds, lower cost of delivering the hydrogen. This is because liquid tanker trucks are more economical than gaseous tube trailers, the delivery method assumed used for LMDV stations. The size of LMDV stations has increased notably in recent years, with new station capacities of around 1,500 kg of hydrogen per day, up from 500 to 1,000 kg per day a few years ago. Recently built LMDV stations increasingly use liquid storage and refueling. This makes their cost structure more like that of HDV stations, though they still operate on a much smaller scale. Our assumption of gaseous systems here provides a useful contrast, but may turn out not to be the main approach used at many refueling stations, as stations get larger.

We estimate that, between 2030 and 2045, system improvements will lower costs. These include increasing station sizes, economies of scale in component production—especially if systems around the country are built—and increasing utilization of stations. The average utilization rate increases to 80% of daily capacity (Table ES-1). This represents a well-optimized system. This happens sooner for HDV stations, mainly due to the higher demand for hydrogen per refueling per vehicle for trucks than cars.

These estimates do not include the cost of hydrogen production, which is mostly outside the scope of this report. Hydrogen could be produced and stored for $2/kg by 2030, based on the Department of Energy's (DOE) production goal of $1/kg by 2031 (DOE 2021). Therefore, the overall cost of producing and delivering hydrogen to vehicles in our Base Case is $8/kg for LDVs and $5/kg for HDVs in 2030. Taking into account fuel cell vehicle efficiency advantages over gasoline vehicles, these costs should be competitive with gasoline and diesel fuel at around $4/gallon for those fuels. This is before applying any government incentives for hydrogen fuels (or taxes for any fuel). Further, the LDV hydrogen cost would be lower in the High Case, given better station utilization and more scale economies. A viable end-user price should be achievable sooner, making low carbon hydrogen cost competitive—especially with added incentives such as the Low Carbon Fuel Standard (LCFS) and Inflation Reduction Act (IRA) production credits. The impact of these incentives will depend on several factors affecting their specific values. Estimating these is outside the scope of this paper, but an important topic for a follow-on paper. Before 2030, costs will be higher and such incentives will certainly be needed to make prices to the consumer competitive with gasoline or diesel. By 2035, and perhaps sooner, electrolytic hydrogen production costs may drop to $1/kg. Along with on-going reductions in transportation and station costs, the system could provide retail hydrogen to vehicles for $4 to $5/kg, which should be highly competitive without any subsidies (Figure ES-3).

This cost analysis has considered a Base Case and High Case, which depend on many assumptions. Costs in 2030 could be higher if actual capital or operating costs are higher, station utilization rates are lower, and/or delivery system costs are greater. Costs could alternatively be lower if growth in hydrogen demand grows rapidly, such as in our High Case. As more stations are built and more vehicles are sold in the coming 2 to 3 years, the picture for 2030 market size, costs, and prices will become clearer.

Before then, to speed market growth, FCEV prices and hydrogen costs must be brought into a competitive range with costs for gasoline and diesel vehicles. Current policies, such as California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project and Low-carbon Fuel Standard (LCFS), and US federal IRA tax credits will help vehicle and hydrogen economics. However, they may not be sufficient to reach cost parity in the near term, in which case further support for vehicle, station, and/or fuel costs may be needed for at least a few years.

Labor Analysis Summary

To provide a rough forecast of labor requirements for a hydrogen system buildout, the UCLA Luskin Center for Innovation estimated the workforce effects of capital and fuel cost spending between 2023 and 2045 with economic input/output modeling. This analysis examines the two core economic areas associated with job creation in California: (1) manufacturing of FCEV transit buses and (2) fuel costs. We project job numbers separately for the Base and High Case scenarios considered in this study.

Key findings

- By 2045, the manufacturing and sales of FCEV transit buses within California are expected to generate between 200 and 300 in-state, full-time equivalent jobs (FTEs), depending on the scenario. Most job growth in this area occurs by 2035.
- In 2030, hydrogen fuel expenditures are expected to produce between 629 and 2,193 FTEs, with this range growing to between 8,169 and 25,518 FTEs by 2045.

- Fuel consumption volume is the key factor in determining job creation. The High Case scenario, with its greater consumption, creates an order of magnitude more jobs than the Base Case scenario. Increased local production – reflected in the 100% LPP scenario – results in smaller, but still significant, job creation gains compared to the default scenario.
- When examining the most heavily represented industries among direct and indirect created jobs, the dominant job creation area is related to the purchase of FCEV transit buses. This provides jobs in electrical equipment and component manufacturing. The quality of these jobs is mixed in terms of wages and access to benefits.
- Fuel consumption creates significantly more job growth than FCEV manufacturing. These jobs are concentrated among trucking, industrial gas manufacturing, and architectural and engineering service sectors.

Contents

Introduction

California is moving toward developing a full renewable clean hydrogen system with its ARCHES (2023) hydrogen partnership approved for funding by the Biden Administration (Whitehouse, 2023) and the US Department of Energy's hydrogen hubs program (DOE, 2023). The transition in California will include adopting hydrogen FCEVs, which has been underway for LDVs for several years and will begin for HDVs in 2024. Around 15,000 light-duty passenger FCEVs are in operation, with around 50 stations to support them. Transit fleets are increasingly deploying and ordering FCEBs and truck manufacturers have started introducing heavy-duty FCETs. ARCHES will support construction of refueling stations and scaling up of renewable clean hydrogen production and distribution systems oriented toward heavy-duty FCEBs and FCETs, along with other end uses, such as port equipment and electric power generation.

There are, however, major uncertainties in how fast these end uses can develop. Their roll-out will affect how fast hydrogen supply and distribution systems for these markets will need to be built. Aligning supply, station construction, and FCEV purchases remains an on-going "chicken-or-egg" challenge. The cost of investments per-unit cost of hydrogen produced and reaching consumers are major concerns. Just considering hydrogen for passenger cars and trucks, the system of refueling stations and delivering hydrogen to these stations is complex and could be developed in any number of ways.

Few studies for California have laid out pathways to a complete statewide system, particularly with a spatial approach. Our previous report, *California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-neutral California*, provided several scenarios with spatial planning. This RIMI-funded project builds on those scenarios and focuses on estimating costs for the transportation system, including vehicles, refueling stations, and hydrogen delivery. A range of investment and hydrogen levelized costs are considered. Our major scenarios were recently published in the paper *California Hydrogen Analysis Project: Final Synthesis Modeling Report* (Fulton et al. 2023). Other technical reports have been published on the ITS-Davis Hydrogen and FCEV Projects webpage (ITS-Davis, 2024).

Growth of the hydrogen production and distribution system must be aligned with growth in demand. Setting benchmarks for numbers of FCEVs on the road by specific dates will enable strategic planning for hydrogen station construction and fuel delivery. System planning must include near term (e.g., to 2030) and longer term (e.g., to 2045) steps. In addition, cross-cutting work on hydrogen system impacts on workforce and social equity must happen simultaneously.

This report discusses spatial planning, costs of FCEVs, and investments required to create a fuel system to supply them. We assess potential numbers of FCEVs by type, where drivers may travel and refuel, how many, where, and what size stations will be needed to support them, where hydrogen might be produced, and how that hydrogen can be delivered. This research is intended to advance the visioning process for a hydrogen-fueled transportation system in California.

Background: Hydrogen System and Fuel-Cell Electric Vehicle Development in California

The State of California has targeted a carbon neutral economy by 2045. As part of this, initiatives for both battery electric vehicles (BEVs) and FCEVs are underway. There are now over one million plug-in hybrid electric vehicles (PHEVs) and pure BEVs in the state. The hydrogen vehicle system is nascent. However, investments and interest are growing. The 2023 announcement from the US DOE that it will fund ARCHES as a hydrogen hub project increases the urgency of developing more specific plans about what this system may look like and cost. Heavy-duty FCETs are a core component of the hub, so understanding FCEV sales growth across classes and hydrogen demand trajectories is central to the planning effort.

California's future could include large numbers of both BEVs and FCEVs powered by low-carbon energy. BEVs and FCEVs may compete in some applications while having complementary roles in others. Due to this, the availability of both light-duty and medium-heavy-duty FCEVs may bolster hydrogen vehicle markets. Many more LMDVs are needed than HDVs to reach a given hydrogen fuel demand level, given much lower hydrogen use per vehicle, but the potential market for LDVs is much bigger.

Depending on usage patterns, BEVs and FCEVs might add to electricity demands, further stressing a renewable-intensive grid. Or they may offer opportunities for energy storage and system management, with electrolytic hydrogen production providing seasonal storage. Other hydrogen end uses, such as power plants, port equipment, aviation, and shipping may increase significantly over time. These must be accounted for in an analysis of hydrogen demands in the state.

Our policy analysis identifies mechanisms to achieve our scenario milestones. The ramp up of hydrogen fuel supply, demand, and sales of FCEVs are very aggressive in our High Case scenario. This use level will not occur without strong policy support. Policy levers include expanding or strengthening existing policies such as the LCFS, cap-and-trade, and ZEV mandates, and/or new approaches, such as investments in infrastructure, fleet vehicle purchase fees and incentives ("feebates").

Hydrogen Studies that this Project Builds Upon

Over the past four years, there have been several hydrogen-related modeling projects for California. Besides our own modeling report, there are six that we used extensively in developing our models and scenarios:

- *Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California* (Reed 2020). This study focused on transitioning to a hydrogen energy system in California across all end-use sectors and presents a roadmap for the buildout and deployment of renewable hydrogen production plants.

- *Getting to Neutral: Options for Negative Carbon Emissions in California* (Baker et al. 2020). Lawrence Livermore National Lab researchers provided a comprehensive analysis of technologies that can enable a carbon-neutral economy and pathways to get there. It assesses carbon capture and sequestration in plants and natural lands as well as underground storage. It also covers reduced carbon-intensity energy systems and puts considerable focus on gasification of biomass to produce hydrogen as a least-cost method for achieving carbon neutrality.
- *Achieving Carbon Neutrality in California* (E3 2020). In a study for CARB, Energy + Environmental Economics (E3) consulting firm provided a set of scenarios for achieving carbon neutrality across sectors. E3 uses their PATHWAYS model and focuses on scenarios achieving at least an 80% reduction in carbon dioxide (CO_2) emissions, balancing this with measures such as land management to remove CO_2 from the atmosphere. They produced three scenarios, ranging from 80% to 100% reductions, with carbon neutrality achieved through carbon-removal measures. Transportation emissions are reduced by anywhere from 85% to 100%.
- *LA 100 Study* (Cochran, 2021). Researchers evaluated renewable energy futures in the City of Los Angeles, reaching 100% renewable sources in some scenarios. The role of hydrogen as a storage and electricity generation component was found to be important, though more expensive than using biofuels.
- *Hydrogen Station Self-Sufficiency Report* (CARB 2021). This study suggests that H_2 stations could reach full economic self-sufficiency by 2030 if around $300 million are spent to help achieve construction of 200 or more stations, and if there are enough FCEVs in service to support these stations economically.
- *2022 Scoping Plan* (CARB 2022a). This plan lays a blueprint for getting to a net-zero carbon future in California. Among other things, it shows a pathway leading to 100% ZEV sales for LDVs by 2035 and for heavy-duty trucks by 2040, with considerable numbers of FCEVs as part of the ZEV mix. It also describes policies and levels of investment needed to achieve targets.
- *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development* (CARB 2022b). This report updates CARB's 2021 station and fuel cell vehicle status report and provides an analysis of trends, and whether on track to meet future targets.

Among peer-reviewed journal articles, we identify two that are highly relevant, though one is dated and the other does not provide detailed estimates of costs as we do here. These are:

- *Determining the Lowest-cost Hydrogen Delivery Mode* (Yang and Ogden 2007). In this article, authors discuss lowest-cost methods for delivering hydrogen from production locations to stations, taking into account distances and delivery chains (e.g., compression or liquefaction, delivery by truck or pipeline, and refueling stations). Compressed gas truck delivery appeared best for small/low demand stations, while liquid delivery was best for long distance delivery and moderate demand. Pipelines appeared best for densely developed areas with a large hydrogen demand.

- *Low Carbon Scenario Analysis of a Hydrogen-Based Energy Transition for On-Road Transportation in California* (Vijayakumar et al. 2021). This study used a transportation transition model to evaluate two scenarios of FCEV adoption and resulting hydrogen demand (low and high) up to 2050 in California. The authors estimated the number of hydrogen production and refueling facilities required to meet demand. It provides some foundational analysis for our current study.

Cost Analysis Methodology

Modeling potential hydrogen systems across supply and demand sectors is a complex undertaking. Developing a credible yet sufficiently detailed analysis is challenging. There are many possible configurations of hydrogen systems and small changes in technology or cost assumptions can have a significant impact on results.

ITS-Davis relied on several analytical tools and models to consider the roll out of a hydrogen system in California out to 2050. These tools supported a highly detailed study of the development of a hydrogen system and system components. To further inform our modeling effort, we conducted a literature review and analysis of technologies and fuels. We continue to advance knowledge of FCEVs and hydrogen as a fuel with our hydrogen and fuel cell vehicle projects (ITS-Davis, 2024).

This effort has included:

1. Development of databases of cost estimates for key components (e.g., hydrogen transportation and storage, refueling equipment), based on the literature and raw data.
2. Characterizations of technology for existing and future FCEVs including updated cost analyses and projections.
3. Characterization of station types and costs using Argonne National Laboratory’s hydrogen refueling station simulation tools (HRSAM, HDSAM, and HDRSM, ANL 2024) to model refueling station configurations and costs. The National Renewable Energy Laboratory (NREL 2019) SERA Model and related research also serves as a basis for our cost estimates.
4. Development of Base Case and High Case scenarios projecting fuel cell LDVs, MDVs and HDVs sold in California, and resulting stock build up, with milestones in 2030, 2035, and 2045. Only the Base Case is considered in this report.
5. Estimates of average station numbers and sizes which ramp up roughly in line with a separate spatial analysis (Fulton et al., 2023).
6. Estimates of hydrogen needed to meet station demand and possible locations of production around the state or outside the state. Here, we assume production is undertaken within the

state, at locations that are, on average, 100 miles from stations. Stations may be nearer to each other than this, so delivery trucks may, in some cases, be able to serve several stations in one trip from the production location. This depends on whether the hydrogen is moved by truck or trailer. Multiple deliveries are only possible with trucks, because trailers are left at stations, requiring a return to the production site to pick up another trailer.

7. An exploration of the use of storage terminals for large quantities of hydrogen delivered from production sources.
8. Consideration of supply end uses on a “last mile” basis, particularly once large numbers of stations have been constructed.

Overview

This study provides step-by-step estimates of needs and costs for the creation of a robust hydrogen fueling system for road transportation in California. The following sections describe scenarios and costs associated with each link in the supply chain. The cost of hydrogen investments and supply to end users are tallied, and we conclude with an analysis and discussion of the labor impacts of hydrogen system development.

The Base and High Case Scenarios

The sales of LDV and HDV BEVs and FCEVs over time, along with resulting stock growth, were projected. Our approach incorporated the UC Davis Transportation Transitions Model (TTM), California policies such as the ZEV mandate(s), and a combination of vehicle choice modeling and heuristics.

The TTM projects sales and stocks in a relatively straightforward manner (Fulton et al. 2023). For example, FCEV sales for different vehicle types are essentially a function of (1) total sales of that vehicle type, (2) the share of vehicle sales expected to be ZEVs, as regulated by the state, and (3) assumptions about the share of these ZEVs that may be fuel cell electric rather than battery electric.

Each of these aspects was modeled for nine different vehicle types and projected for Base and High Cases in 2030 and 2045 (Figure 1).

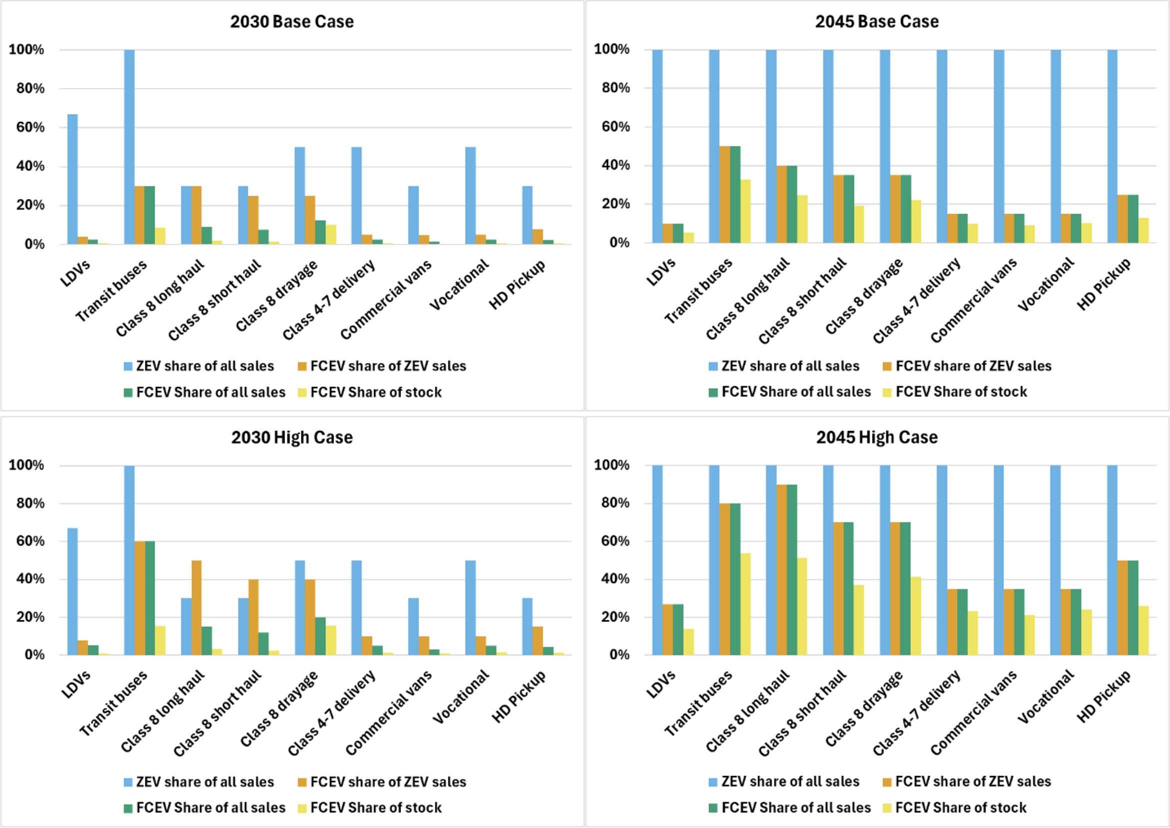

Figure 1. ZEV shares of sales and stock and FCEV shares of ZEVs for 2030 (left) and 2045 (right) in Base Case (upper) and High Case (lower) scenarios. Bars represent a) ZEV vehicle share of all LDV sales (rising to 100% by 2035 and beyond), b) FCEV share of ZEV sales, c) FCEV share of all sales (equal to the share of ZEV sales once ZEVs are 100% of sales), and d) FCEV share of the total stock of vehicles (with the lag from stock turnover).

Base and High Case Assumptions

In the Base Case, by 2030, the ZEV share of total sales reaches nearly 67% for LDVs, 100% for transit buses, and anywhere from 30% to 45% for various truck types. The FCEV share of ZEVs, and thus of total sales, is typically quite low at about 5% for LDVs and other smaller trucks and at 25% or 30% for larger trucks and buses. These sales shares determine the actual sales in this scenario and were set to provide a plausible yet significant trajectory for FCEV sales – enough to support the development of a large refueling system.

By 2035, all vehicle types sold will be required to be ZEVs. Most of these are assumed to battery electric and we assume FCEV share of ZEVs rises until about 2040 when it reaches an equilibrium share of ZEV, they reach somewhat higher sales; this share varies by vehicle type but is typically around double the 2030 share. LDVs are lowest at around 10%; transit buses and heavy-duty trucks are highest at 50%, and medium-duty trucks range from 10 to 20% of ZEV sales.

In the High Case, FCEVs reach much higher sales shares by 2030 and beyond; roughly twice the shares seen in the Base Case. High Case sales shares rise to three times the Base Case shares by 2045 for LDVs and some medium-duty truck types. Heavy duty trucks and buses, which reach 50% sales shares in 2045 in the Base case, increase to 80% in the High Case. These higher sales shares result in proportionately higher stock shares by 2045 with over 20% for all except LDVs, which reach about 17%.

Vehicle Types and Sales Assumptions

By 2040, all vehicle types sold will be required to be ZEVs. We assume FCEVs have reached an equilibrium share of ZEV sales by then, which varies by vehicle type. LDVs are lowest at around 10%, transit buses are highest at 50%, and trucks range from 20 to 30% of ZEV sales. This picture remains fairly constant to 2050 (although stock shares still rise, presumably).

Given the assumptions and calculations made in the model, the two vehicle types with the highest demand for hydrogen were LDVs and long-haul trucks (Table 1). Base Case assumptions and calculations use this information to get from vehicle sales, to stocks, to hydrogen use in a given year. Sales growth for both types of vehicles is rapid from 2024 to 2030 and beyond. The combined hydrogen demand from these two vehicle types in 2030 is about 275 tons/day which, when combined with other vehicle types, reaches about 375 tons/day. Thus, these two vehicle types represent a high share of the combined demand of all types in 2030. These projections are the basis for hydrogen demand estimates.

Table 1. Base Case scenario assumptions for LDVs and long-haul trucks by year.

LDVs	2024	2027	2030	2035	2040	2045
Total LDV sales (millions)	1.8	1.8	1.9	1.9	1.9	1.8
ZEV sales share	25%	35%	67%	100%	100%	100%
FCEV sales share of ZEVs	0%	2%	4%	5%	7%	10%
FCEV sales (thousands)	1	10	50	93	130	178
FCEV stock (thousands)	16	31	118	427	853	1,318
Hydrogen (kg/vehicle/day)	0.70	0.70	0.70	0.70	0.70	0.70
Hydrogen (tons/day)	11.3	21.6	82.7	298.3	595.9	920.6
Hydrogen (thousand tons/year)	4.1	7.9	30.2	108.9	217.5	336.0

Long Haul Trucks	2024	2027	2030	2035	2040	2045
Total sales (thousands)	12.6	13.0	13.4	13.6	13.8	14.0
ZEV sales share	5%	15%	30%	50%	100%	100%
FCEV sales share of ZEVs	15%	25%	30%	40%	40%	40%
FCEV sales (units)	45	484	1,206	2,720	5,520	5,600
FCEV stock (units)	50	675	3,217	11,734	27,788	44,135
Hydrogen (kg/vehicle/day)	60	60	60	60	60	60
Hydrogen (tons/day)	0.3	40.5	193.0	704.1	1,667.3	2,648.1
Hydrogen (thousand tons/year)	0.1	14.8	70.4	257.0	608.6	966.6

Hydrogen Demand

The growth in hydrogen demand is very rapid, especially after 2030, reaching 6,000 tons/day (2 million tons/year) by 2050 in the Base Case and 14,000 tons/day (4.5 million) in the High Case (Figure 2). The early growth is also significant, reaching several hundred tons/day by 2030, compared to 10 to 15 tons per day by LDVs in California in 2024. In the High Case, hydrogen demand in 2030 reaches 900 tons/day about three times the base case in 2030. The High Case also reaches more than double the Base Case in 2045.

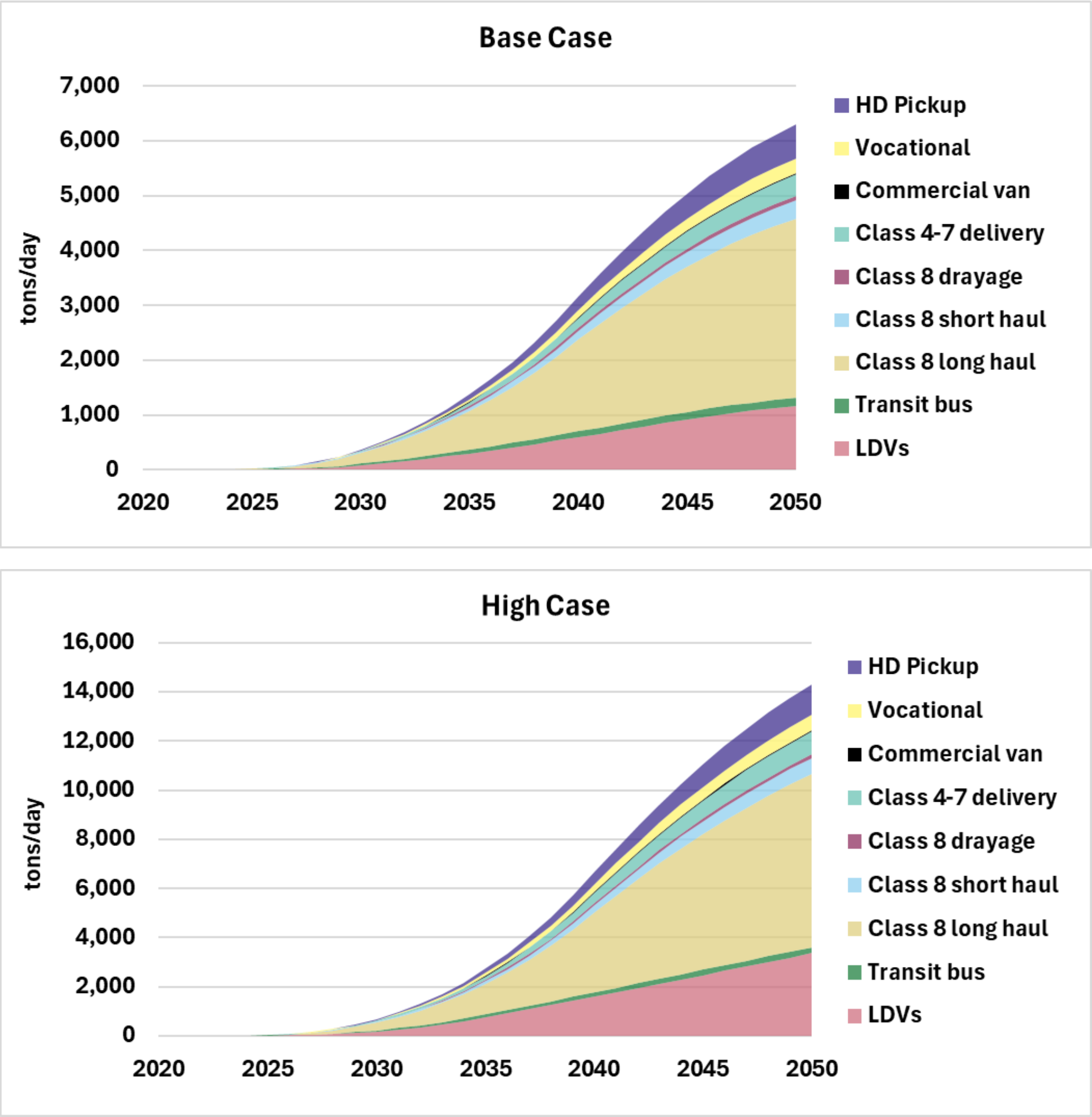

Figure 2. Hydrogen demand to 2050 in the Base Case (top) and High Case (bottom), tons/day.

The Cost of Fuel Cell Electric Vehicles

The cost of purchasing FCEVs can be measured in absolute terms, as costs in excess of what would have been spent on diesel or gasoline vehicles, or relative to purchasing BEVs. Based on UC Davis data and estimates of vehicle production costs and prices (e.g., Burke et al, 2023), we project all these types of costs into the future. This takes into account expected declines in FCEV and BEV prices due to cost declines in components such as fuel cell systems and more general “learning” and optimization-related cost reductions as well as production volumes increasing in accordance with scenarios. We use the same cost assumptions in our Base and High Case scenarios because (1) there appears to be enough volume in the Base Case to justify cost reduction equivalent to the High Case and (2) there may be large sales volumes in other parts of the US and internationally which will bolster economies of scale, particularly related to the supply chain of key components. We use inflation adjusted “real” prices throughout this paper but do not time-discount prices or costs.

Medium- and Heavy-Duty Vehicles

We focus here on FCEV truck and bus vs. diesel truck prices (Figure 3). The costs (prices) of FCEVs across all truck and bus types are quite high from 2020 through around 2025 due to new product introductions featuring expensive cutting-edge technology and very low volume production. Through 2025, we assume typical fuel cell electric truck and bus prices will be up to several hundred thousand dollars higher than diesel equivalents. We then expect these costs to decline steadily through 2035 as optimization occurs and production volumes rise. There is still a significant FCEV cost increment projected for 2030, but prices are mostly equivalent to diesel vehicles by 2035. This “cost parity” point could happen sooner if production volumes and learning rates have bigger impacts than we assume in our analysis.

Light Duty Vehicles

For LDVs including BEVs, both FCEVs and BEVs reach parity on purchase cost with gasoline vehicles between 2028 and 2032, with BEVs a few years ahead of FCEVs (Figure 3). Depending on the battery loadings (capacity) of the BEVs and the long run price of batteries and fuel cell systems, FCEVs are expected to reach purchase price parity with BEVs by the late 2030s. This could happen sooner depending on technology learning and volumes of FCEVs produced in California and around the world.

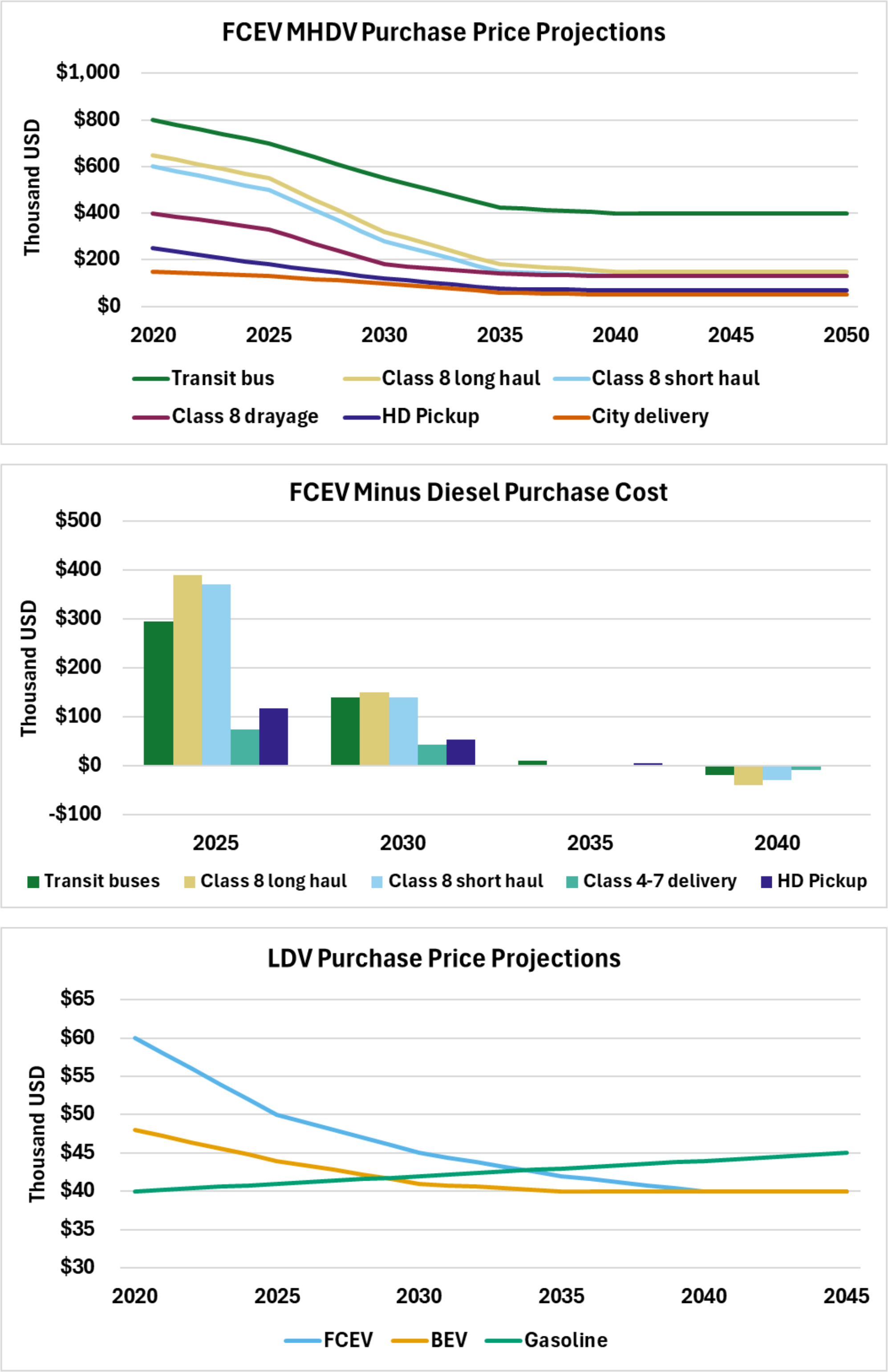

Figure 3. FCEV projected purchase prices and comparisons to other technology options.

Estimated Investment Costs

By multiplying these purchase prices by the number of vehicles purchased in each year, we derive the total annual investments in new FCEVs by vehicle type and overall. For the Base Case, annual investments reach about $4 billion by 2030 and over $10 billion by 2045. Even though the prices of vehicles decline over time, sales rise so much that the total investments rise rapidly over time. Total Base Case investments between 2023 and 2030 are about $10 billion. Adding together all years between 2023 and 2050, the overall total (undiscounted) investments are about $130 billion. Equivalent figures for the High Case are $7 billion spent by 2030 and $28 billion by 2045, with cumulative totals of $21 billion to 2030 and $310 billion to 2045.

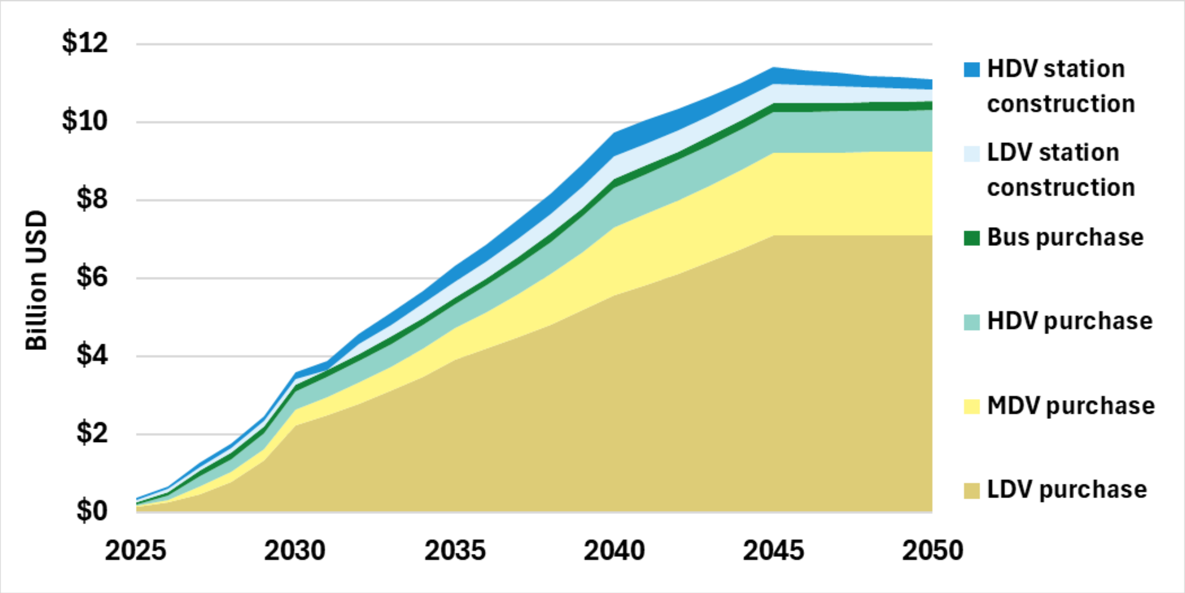

Figure 4. Cumulative Purchase Investment on new FCEVs, Base Case.

Are these investments large? Certainly. However, in the context of the amount currently and projected to be spent on diesel trucks and gasoline LDVs, cost projections suggest the expenditures are moderate and may be lower than the internal combustion engine (ICE) status quo, over time (Table 2). The $9 billion spent on FCEVs sold through 2030 shows in the first column, second row. But the row above shows the total cost of all vehicles sold, if they were ICEs, to give a sense of how much gets spent in a status quo case, even without any ZEV sales. This comes to over $700 billion over the next six years, including both cars and trucks (as do all numbers in the table). The majority of spending is for LDVs yet a significant amount is spent on heavy-duty trucks, as well. If, instead of the FCEVs sold to 2030 in the scenario, these were all ICE vehicles, the cumulative purchase cost would drop from $9.2 billion to $6.9 billion, a savings of $2.3 billion. This is about 0.3% of the total spent on all vehicles (Table 2, first row). The situation is similar if the cumulative totals are extended to 2040 though, by 2040, the total spent over the 17-year timespan is actually less for FCEVs than for ICEs. This is because most types of FCEVs are projected to be cheaper by then (and many by 2035 or sooner) and sales are far higher in 2035 than in earlier years. These numbers are undiscounted, and discounting would make the totals lower into the future and possibly change this 2040 FCEV savings to a small net cost.

Market Shares by Vehicle Type

We have conducted separate accounting for LDVs and MHDVs (Table 2). Results show that LDVs support a far larger market than MHDVs and that the costs/prices of fuel cell electric LDVs are closer to ICE equivalents and reach parity earlier than MHDVs. While the overall investment in fuel cell electric LDVs to 2030 is over $7 billion, the incremental cost over the equivalent number of ICE LDVs is only $0.3 billion. For MHDVs, the equivalent numbers are $1.5 billion and $1.4 billion. In other words, fuel cell electric MHDVs require about twice as much investment to 2030 than if these were all ICE vehicles; $2.9 billion vs. $1.5 billion. However, after 2030, the incremental costs of fuel cell electric MHDVs are quite low.

Table 2. Hypothetical investments for new LDV and MHDV purchases, Base Case ($USD billions).

Vehicles	Scenario	2023 to 2030	2023 to 2040
All vehicles	Cumulative total - if ICEs were all vehicles sold	$712.2	$1,657.3
	Cumulative total – for all FCEVs actually sold	$9.2	$68.7
	Cumulative total - if ICEs sold same numbers as FCEVs	$6.9	$68.2
	Incremental expenditure cost of FCEVs	$2.3	$0.5
LDVs only	Cumulative total - if ICEs all vehicles sold	$621	$1,437
	Cumulative total - All FCEVs actually sold	$5.4	$45.4
	Cumulative total - if ICEs sold same as FCEVs	$4.9	$47.5
	Incremental cost of FCEVs	$0.4	-$2.1
Trucks/ buses only	Cumulative total - if ICEs all vehicles sold	$24.4	$59.7
	Cumulative total - All FCEVs actually sold	$2.5	$11.5
	Cumulative total - if ICEs sold same as FCEVs	$1.3	$10.3
	Incremental cost of FCEVs	$1.2	$1.2

Market Shift

The overall message is that, while there could be on the order of $2 billion in incremental costs associated with shifting from diesel to fuel cell electric vehicles through 2030, this is a small share of the total that will be spent by the public on new vehicles. Spending on new vehicles is anticipated to be over $700 billion in California through 2030. After that, LDV FCEVs are expected to be, on average, cheaper than ICEs, with FCEV trucks becoming cheaper at some point in the 2030s.

Hydrogen Refueling Station Costs

Station cost estimates are dependent on the number of stations built, their technologies, their sizes, and their component costs. Changes in numbers and types of stations will affect costs via technology, economies of scale, and learning as more stations are built. For the two cases presented here, results for 2030 and 2045 are presented along with (Figure 5) key inputs (Table 3). Stations are categorized as either (1) those designed for refueling both LDVs and MDVs that can “fit” into light-duty station designs and have similar refueling equipment or (2) those for HDVs, such as Class 8 trucks, which are likely to have larger daily refueling capacities and require more space for vehicles. We also assume that LMDV stations use gaseous storage and refueling systems, while HDV stations use cryogenic liquid systems. This strict difference may not arise, but it serves as a simplifying assumption here. All stations are assumed to receive hydrogen by truck and then store it on site.

For both cases, by 2030, there are 175 LMDV stations and at least 50 HDV stations. In both cases, their construction costs begin to approach long-run costs. Larger HDV stations are cheaper to build, per unit capacity, than LMDV stations. This is due to their larger size and less expensive cryogenic liquid storage and refueling system. Compressed gas, used by the LMDV stations, is more expensive to store and distribute. By 2045, construction costs have dropped somewhat further.

Operation Costs

The cost estimate for operating the stations includes amortizing this construction cost (over 20 years with financing at a 10% interest rate), paying for fixed and variable operating costs, and paying for the hydrogen delivered to the station. Capital costs and fixed operating costs must be spread over the amount of hydrogen processed per day. Hydrogen processed per day is, therefore, an important factor in calculating the overall (or levelized) cost of the station. Stations with a low utilization rate will have higher levelized costs than stations with high utilization (Table 3). We expect low utilization rates for the 175 LMDV stations in 2030 because the number of vehicles per station are estimated to be low, yet many stations are needed to encourage sales of FCEVs and to capitalize on imminent market growth. In contrast, we estimate a much higher utilization rate for HDV stations by 2030. This is due to needing only 50 HDV stations to meet market demand (mostly located along highways), a rapid increase in the number of trucks, a greater demand for refueling per truck, and, thus, lower requirements for trucks-per-station to reach high utilization rates. As a result, HDV station levelized costs are much lower than for the LMDV stations (Figure 5). By about 2035, and certainly in 2045, both station types reach a long-run 80% utilization rate and levelized costs are much lower, under $4/kg processed and sold with retail markup. These are station costs only, and do not include the cost of hydrogen production or transport. HDV stations continue to be cheaper given their much larger average sales volume (nearly 9 tons/day in 2045, vs. 2 tons/day for LMDV stations).

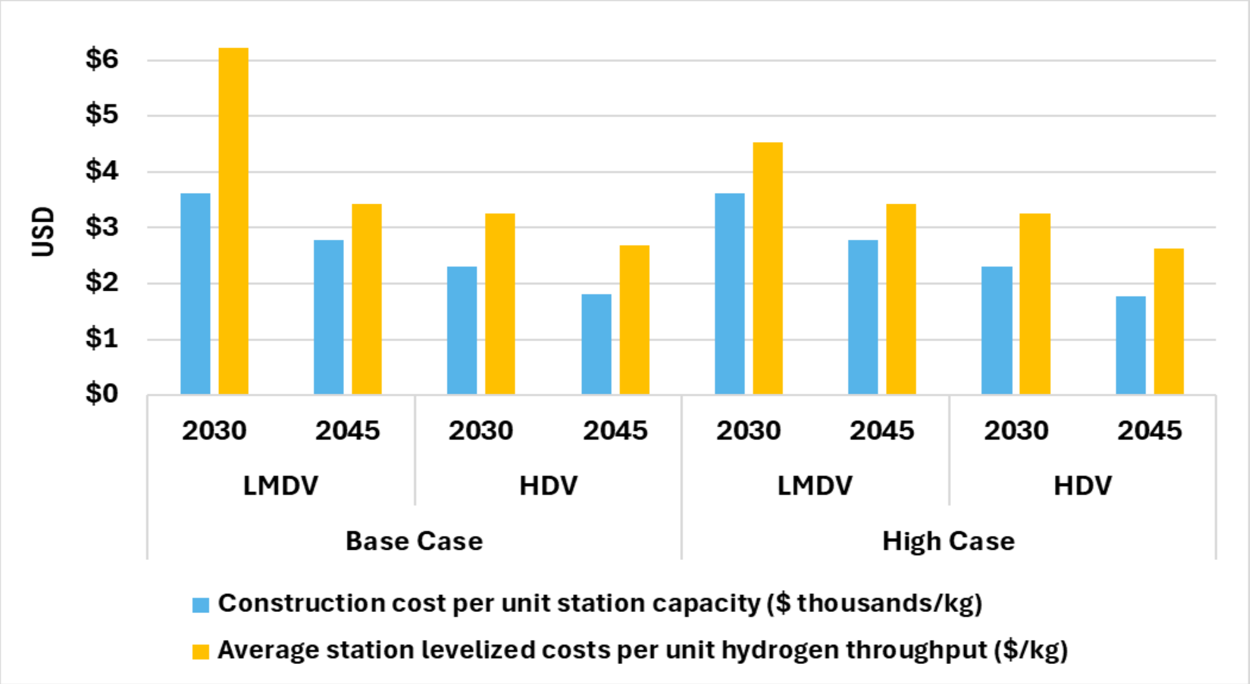

Figure 5. Investment and levelized costs for LMDV and HDV stations (note differing units on y-axis for construction vs. levelized station costs).

Table 3. Assumptions and cost projections for hydrogen LMDV and HDV stations, 2030 and 2045.

	LMDV Stations		HDV stations	
Year	2030	2045	2030	2045
Total hydrogen dispensed (tons/day)	129	1,927	217	2,977
Number of stations	175	1,128	59	428
Number of vehicles per station	735	1,351	70	132
New station capacity (tons/day)	1.5	2.5	5	10
Average station capacity (tons/day)	1.3	2.1	4.6	8.7
Average utilization rate (%)	56%	80%	80%	80%
Construction cost per unit station capacity (USD/kg)	$3,600	$2,800	$2,300	$1,800
Construction cost per new station (million USD)	$5.4	$7.0	$11.5	$18.1
Total construction cost in year (million USD)	$146	$500	$162	$435
Cumulative construction cost through year indicated (million USD)	$968	$7,523	$651	$7,383
Average station levelized costs per unit hydrogen throughput (USD/kg)	$4.7	$2.6	$2.5	$2.1
Station cost plus retail markup, with full cost recovery (USD/kg)	$6.1	$3.4	$3.2	$2.7

Construction Costs

The cumulative construction investment cost in 2030 is nearly $1 billion for LMDV stations and $650 million for HDV stations (Table 3). This rises to about $7.5 billion for LMDV stations and $7.4 billion for HDV stations from 2023 to 2045. The sum is $15 billion for all stations built over the 22 years studied. For about 1,560 LMDV and HDV stations, the average cost per station would be around $9.6 million.

Hydrogen Fuel Shipments and Delivery

In order to more fully characterize hydrogen costs for transportation end uses, we also look at the costs of moving fuel from hydrogen fueling locations to stations, focusing on truck delivery. We assume all hydrogen is moved from production sites to stations through 2045 via gaseous delivery trucks with “tube trailers” for LMDV stations and with cryogenic liquid tanker trucks for HDV stations.

Capacity

The use of gaseous hydrogen tube trailers is problematic for large stations. This may lead to liquid delivery and storage at LMDV stations, as appears to be increasingly the case for newer LMDV stations and is likely for most HDV stations. It is possible that larger gaseous storage capacities on trucks/trailers could be developed. These have doubled in capacity in the past few years, from typically 400 up to 800 kg. If a trailer with a 1,500 kg capacity, for example, were developed, this would be suitable for resupplying even the largest LMDV stations included in our scenario. Around three tons per day could be delivered with two trailers, meeting demand on busy days. For HDV stations eventually selling eight tons per day or more (maximum 10 tons/day by 2045 in our scenario), this approach still would be very cumbersome. Liquid tankers carrying 4 tons, already operating, could serve the largest stations with two shipments per day, except on the busiest days.

Ultimately, a pipeline system may be needed to provide a steady, large volume flow of hydrogen to all stations. Although we anticipate this possibility, we do not consider pipelines in this paper. They will be considered in future research.

Trailer Logistics

For hydrogen stations serving MHDVs, trucks towing tube trailers are assumed to drop off trailers full of hydrogen at stations. As trailers are emptied, new ones are provided. This means only one trailer is needed at a station at a time and there is always one tube trailer at each station. Well-coordinated trailer deliveries will be necessary to ensure a reliable supply.

The system is assumed to require a total number of trailers equal to one per station and sufficient additional trailers to always have one ready at a central hydrogen recharge facility for a truck to then tow it to a station in need. This calculation could be complex but is simplified here. We assume that, during the phase-in of hydrogen fuel systems, 20% more trucks than the total number of stations will be needed. As the system matures, there will eventually be one trailer per station plus at least one per truck. Trailers are assumed to become slightly larger over time, maxing out at 1000 kg by 2030, with the price of such trailers dropping to $400k by 2030 and $300k by 2045. The cumulative investment cost for this system including trucks and trailers is about $70 million by 2030, and over $700 million by 2045.

Tanker Truck Logistics

For LMDV stations, cryogenic liquid tanker trucks provide refueling as needed and no trailers must be bought. The cost of these trucks is around three times the cost of a tractor for pulling trailers. This is still far less expensive than a system of tractors and tube trailers. Given their relatively large capacity of 4 tons, the same truck could serve several stations during the hydrogen phase-in, when stations do not sell anywhere near their full station capacity in a day. As utilization increases, each truck can serve fewer stations in a single trip, until eventually it is serving one station, then returning to a "base" hydrogen facility to refuel for the next station. Depending on trip lengths and travel times, one truck still could make two or three deliveries each day, refilling at base after each one, or serve a single 8 ton/day station twice in a day. As no equipment is left at stations, liquid tanker trucks can serve many more stations than tube trailers. The number of liquid tanker trucks rises relative to stations over time but, even in 2045, 433 trucks are estimated to be sufficient to serve 428 stations (Table 4).

Comparing Costs

The resulting cost of these trucks is far lower than for LMDV station tube trailer systems, with a cumulative investment cost of $27 million by 2030 and $413 million out to 2045. A tanker truck system at this scale would deliver more fuel per day than gaseous trucks in the LMDV system.

Taking into account operating costs of these vehicles and the delivery system, the net cost per kg delivered is also far lower for the liquid truck system at around $0.19 per kg, whereas the LMDV system costs $0.89 per kg in 2030 and drops to $0.57 per kg by 2045. Prices for a LMDV system reflecting some economies of scale but are still far more expensive than the HDV station liquid truck system

Table 4. Delivery assumptions and costs for trucking hydrogen to LMDV and HDV hydrogen stations.

	LMDV stations		HDV stations	
Year	2030	2045	2030	2045
Truck type used	Gaseous tube trailers		Liquid tanker trucks	
H_2 delivered to all stations per day (tons)	129	1,927	217	2,977
Number of stations	175	1,128	59	428
H_2 delivered per day per station (kg)	739	1,708	3,670	6,956

	LMDV stations		**HDV stations**	
Year	**2030**	**2045**	**2030**	**2045**
Truck type used	**Gaseous tube trailers**		**Liquid tanker trucks**	
Avg H_2 deliveries per delivery truck per day	4.0	4.0	2.0	1.9
H_2 provided per delivery truck per day (kg)	2,400	4,000	7,370	7,579
Delivery truck/trailer capacity (kg)	800	1,000	4,000	4,000
Delivery trucks needed	54	636	31	433
Trailers needed	247	1,877	31	433
Truck (tractor) price (thousand USD)	$221	$150	$221	$150
H_2 trailer price (thousand USD)	$298	$288	$500	$500
Cumulative investment cost, all trucks/trailers, 2023 through year indicated (million USD)	$70	$840	$27	$413
Levelized capital/operating cost per kg delivered	$0.89	$0.57	$0.19	$0.18

Total System Costs

An estimate of the total costs of a hydrogen distribution system can be made by summing the costs of the vehicles using hydrogen, stations that dispense it, and delivery to stations. This excludes costs such as hydrogen production and storage and/or terminal costs “upstream” from this system. These costs should be added in for fuller accounting of investment requirements and average cost of per-unit hydrogen delivery to vehicles.

The cumulative “investment” (purchase) cost of the vehicles themselves represents by far the biggest cost of this system (Table 5). These investments represent around $9 billion between 2023 and 2030 when adding together LMDVs and HDVs. About 80% of the costs of the LMDV category is for LDV purchases by households, rather than for medium duty trucks.

These vehicle purchase costs reflect the actual expected purchase prices which are currently high and are expected to decline significantly over time. By 2030, we expect that fuel cell LDVs will be cheaper to buy than conventional gasoline vehicles and fuel cell truck prices will approach those of diesels. Fuel Cell truck prices are expected to be considerably more expensive in 2030 and then reach parity in the early 2030s. However, if one considers only these incremental costs of the FCEVs over comparable gasoline or diesel vehicles, the net investment numbers drop dramatically. For cars and trucks together, these fall from around $9 billion to well under $2 billion in the 2030 timeframe (Table 5). Looking out to 2045, the net purchase costs are negative for LMDVs, while still positive for HDVs. However, the HDV FCEV incremental costs do not rise much between 2030 and 2045, indicating they are about equal to diesel costs after 2030.

Vehicle costs are important in the early years because the initial cost of purchasing end-use cars and trucks is far higher than investment costs for stations and hydrogen delivery equipment. Through 2030, investment costs for LMDV stations are about 1/7—and delivery equipment costs are about 1/100—of vehicle costs. The ratios are somewhat higher for HDV stations and begin to approach the cost of vehicles by 2045. For both types of stations, if only the incremental costs of vehicle purchase are included, net vehicle costs eventually become lower than the stations serving them.

Table 5. System investments by category, cumulative through indicated year, Base Case (million USD). The FCEV "incremental over diesel" metric is an alternative to "total vehicle purchase," with separate totals in green.

	LMDVs		HDVs	
	2023-2030	2023-2045	2023-2030	2023-2045
FCEV (total vehicle purchase)	$6,693	$56,391	$2,461	$11,521
FCEV (incremental over diesel)	$414	($2,123)	$1,178	$1,220
Refueling stations	$968	$7,523	$651	$7,383
Delivery vehicles	$70	$840	$27	$413
Total investment cost	$7,731	$64,753	$3,139	$19,316
Total with incremental vehicle investment cost	$1,452	$6,240	$1,856	$9,015

Labor Analysis of Scenarios

To provide a preliminary forecast of the labor ramifications of the hydrogen buildout showcased in this study, the UCLA Luskin Center for Innovation used economic input/output modeling to estimate the job creation effects of associated capital and fuel cost spending between 2023 and 2045. This analysis examines the two primary economic areas associated with job creation in California: (1) manufacturing of FCEVs (transit buses, specifically) and (2) fuel costs. Job numbers are provided for the Base and High case scenarios. The focus on transit buses and exclusion of trucks in the vehicle production analysis is because only fuel cell electric buses are being, or are expected to be, produced in the state. Fuel cell electric truck manufacturing is not anticipated. Should other FCEV classes be manufactured in the state, we would expect additional job creation.

Background and Limitations

This analysis is premised on the use of economic input/output (I/O) modeling. I/O modeling uses data-based mapping of industrial sector relationships to estimate how economic activity (i.e., monetary expenditures) in one sector or group of sectors translates to job creation across the economy. For example, activity in one area (e.g., FCEV manufacturing) can catalyze growth in related sectors throughout the supply chain. Industries that provide necessary manufactured goods (e.g., electronic components) or raw materials (e.g., refined metals) may be affected. I/O modeling also captures the generalized job benefits to the greater economy as workers spend their wages on good and services.

Modeling output categories are as follows:

- *Direct jobs* are those created in the immediate industries of interest (e.g., employees at a hydrogen refueling station).
- *Indirect jobs* are those created in supply chain-linked industries (e.g., mechanics servicing trucks carrying hydrogen fuel to stations).
- *Induced jobs* are those supported throughout the broader economy by the activity generated by newly created direct and indirect jobs (e.g., everything from gardeners to health care professionals to movie theater attendants).

Model outputs are provided in the form of full-time equivalent jobs, or FTEs. One FTE accounts for the labor activity of one employee working full time for one year. However, this does not necessarily mean that the job will take that form. Equivalent output could be produced by two workers employed part-time at 50% for one year, two workers employed full time for six months, and so forth.

Some limitations of I/O models may affect the interpretation of results:

- I/O models utilize *static relationships* based on economic conditions at a certain point in time. Our analysis was conducted utilizing the IMPLAN 2022 California State Total data package

(IMPLAN 2022). The results obtained assume that economic relationships among industries persist in their current state until 2045. No attempt is made to forecast or predict changes that may influence observed outcomes to these relationships.

- The model assumes that workforce impacts *scale linearly*. It does not incorporate potential influences of fixed worker demands or economies of scale. Spending $10 million in Industry X will generate exactly 10 times the labor impact as spending $1 million in Industry X.
- The model does not specify *timing of workforce impacts*. Job impacts are attributed to the year in which spending occurs, but that does not necessarily mean that those jobs will be realized in that year. In the real world, the effects of spending will take time to percolate through supply chains and the economy.

Jobs Analysis: Methods

We calculate spending estimates in the sectors of interest using data from the study scenarios. These expenditures are translated to FTEs using estimated labor intensity figures. Labor intensity refers to how many FTE jobs are created per unit of money spent in a given sector, in this case, measured in FTEs per $1 million. Labor intensity and wages vary across industries. For instance, all other factors equal, if $1 million were spent in a year in a sector where the average worker makes $100,000 annually, this spending would be expected to create fewer jobs than the same amount spent in a sector where the average worker makes $50,000 annually. A given expenditure covers both labor and non-labor cost components, the latter of which may, in turn, have associated labor inputs in other parts of the supply chain. Thus, assessing job impacts requires using a *cost composition* which maps how, when a sum of money is spent in a particular area, that money is distributed among different industries. Based on the traits of each industry and the amount of money flowing to it, the model estimates job creation potential per unit of money spent in each individual economic area.

Here, we use the same cost composition for FCEV sales and hydrogen fuel costs as in our previous transportation decarbonization workforce analysis (Brown et al. 2021). Details are available in a complementary technical report (Coffee et al. 2022).

Combining the cost composition with the model data package produces an overall figure for FTEs per $1 million coefficient by year and job type (direct, indirect, induced) for the areas of interest. Initial inputs of aggregate consumer expenditures are determined using data from the above scenarios. Expenditures on FCEVs are determined through simple arithmetic, by multiplying the number of vehicle sales by vehicle price. Hydrogen fuel consumption expenditures are calculated using hydrogen consumption and cost figures for each of the three covered vehicle classes: LDVs, FCETs, and FCEBs.

Within direct, indirect, and induced job categories, the IMPLAN model can identify job creation figures at the industry level. These industry designations can, in turn, be mapped to industry codes within the North American Industry Classification System (NAICS). This system is used by federal agencies to classify industries and businesses for purposes of economic statistical analysis. Information is provided by IMPLAN. We identify and examine the top five industries within which direct and indirect jobs are created and note trends in how job growth is expected to be distributed among different professions. Using occupation-level, California-specific wage data, and national industry-level data on access to healthcare benefits and representation by unions from the US Department of Labor's Bureau of Labor Statistics (BLS), we characterize the quality of these jobs and identify potential policy-related ramifications in areas including equity and organized labor.

Scenario Inputs

The Base Case number of vehicle sales and hydrogen demand per day are presented in the first section of this paper. Here we show a summary of the Base and High Case scenarios for key variables that the workforce analysis draws upon, namely transit bus stocks and total transportation hydrogen demand. By 2030, transit bus stocks exceed 1,000 in the Base Case and are about 2,500 in the High Case. By 2045, transit bus stocks reach 6,000 in the Base Case and 10,000 in the High Case. In 2030, total hydrogen demand across all vehicle types is around 360 tons/day in the Base Case and 930 tons/day in the High Case. By 2045, hydrogen demand reaches nearly 5,000 tons/day in the Base Case and over 11,000 tons/day in the High Case.

The workforce analysis focused on how producing this number of buses and this much fuel in the state affects jobs (Table 6).

Table 6. Base and High Case Inputs for Workforce Analysis.

	2030		2045	
	Base	High	Base	High
FCEB stock and approximate cumulative sales (thousands)	1.3	2.5	6.4	9.8
Total H_2 demand from all vehicle types (tons/day)	380	933	5,072	11,183

Model Results

In the area of FCEV (namely FCEB) manufacturing, we estimate that, by 2045, the industry will generate slightly over 300 FTEs annually for the High Case scenario or slightly over 200 FTEs annually for the Base Case scenario. Aggregated across the study timeline, from 2023 through 2045, we predict this activity will generate approximately 5,305 FTEs or 3,407 FTEs, respectively (Table 7).

An assumption underlying these figures is that FCEBs for transit will be the only hydrogen vehicle type manufactured within California. Should other FCEV classes be manufactured in the state, we would expect additional job creation not reflected in the results below. We do not address potential indirect or induced jobs that might be created by out-of-state manufacture of FCEVs with reliance, in part, on California firms in their supply chain, nor from in-state sales of FCEVs manufactured elsewhere.

Table 7. Aggregate FTEs from FCEV transit bus purchases by scenario and job type from 2023 through 2045.

Scenario	Direct FTEs	Indirect FTEs	Induced FTEs	Total FTEs
High	2,226.38	1,379.73	1,699.03	5,305.15
Base	1,429.39	886.57	1,090.81	3,406.78

Full Time Equivalent Job Growth Overview

In the High Case scenario, the bulk of total annual FTE growth occurs by 2030. A slower ramp-up under the Base Case scenario leads to almost all annual FTE growth taking place by 2035 and negligible year-over-year growth thereafter. Across both scenarios, direct jobs constitute the plurality of created jobs, and direct and indirect jobs together make up a majority of created jobs. Most of the jobs-related impact of FCEB purchases, therefore, is expected to be concentrated in FCEV manufacturing businesses or, to a lesser degree, firms within their supporting supply chains. Annualized job creation breakdowns show that the High Case scenario produces more jobs sooner and overall (Figure 6).

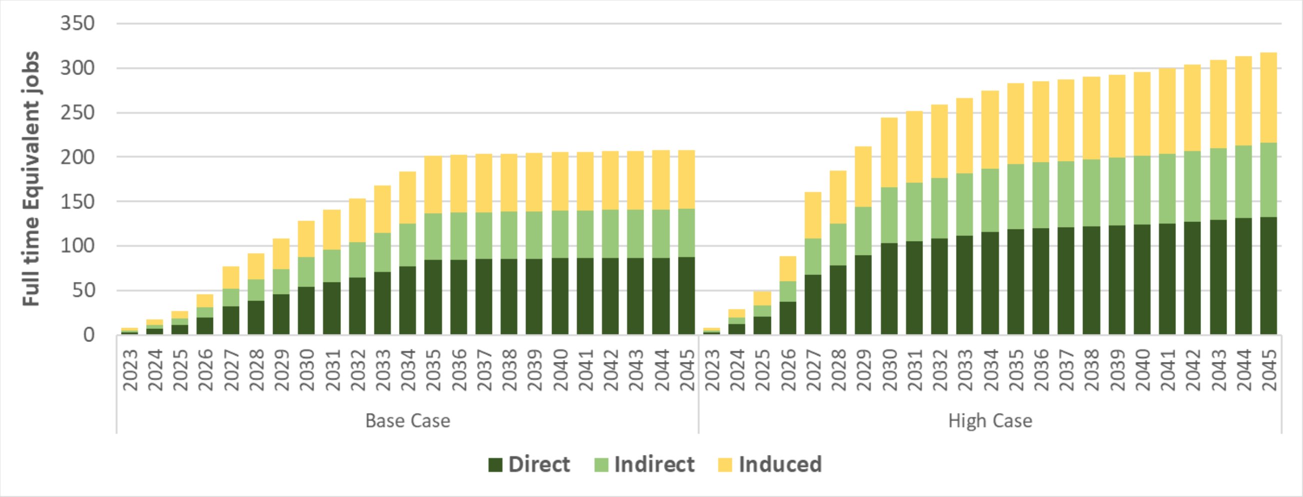

Figure 6. Job creation from expenditures on FCEV transit buses for High Case and Base Case scenarios by job type and year from 2023 to 2045.

Among direct and indirect jobs, the highest-growth occupation by a large margin is direct jobs in "All other miscellaneous electrical equipment and component manufacturing" (NAICS 335999). The model estimates growth in this occupation to be approximately 0.185 FTEs per $1 million (FTE/$1M), an order of magnitude higher than the second-highest growth direct occupation and the highest indirect job occupation. Numbers for the top five growth occupations among direct and indirect jobs created by FCEV transit bus purchases show new manufacturing jobs being created across a plethora of industries (Table 8). There are smaller numbers of indirect jobs that tend more towards administrative, managerial, and sales positions.

Table 8. Top five direct and indirect growth occupations from FCEV transit bus purchases.

IMPLAN Occupation	NAICS Code	FTE/$M
Direct		
1. All other miscellaneous electrical equipment and component manufacturing	335999	0.185
2. Metal tank (heavy gauge) manufacturing	332420	0.0475
3. Heavy duty truck manufacturing	336120	0.0341
4. Air purification and ventilation equipment manufacturing	333413	0.0151
5. Motor vehicle body manufacturing	336211	0.0119
Indirect		
1. Employment services	5613	0.119
2. Management of companies and enterprises	55111	0.0095
3. Truck transportation	484	0.0091
4. Wholesale – Household appliances and electrical and electronic goods	4236	0.0090
5. Wholesale – Machinery, equipment, and supplies	4238	0.0081

Jobs Created by Fuel Consumption

Considering jobs created from recurring hydrogen fuel consumption we estimate that, by 2045, hydrogen fuel expenditures will undergird the creation of a significant number of jobs in California. The fuel-related jobs estimate is one to two orders of magnitude greater than our estimate of jobs related to FCEV sales in that year (Figure 7). Unlike our analysis of FCEV sales-related jobs, the underlying data does not allow us to provide yearly FTE results. We instead provide figures for 2030 and 2045.

This analysis incorporates an additional dimension to the Base and High Case scenarios: Default versus 100% local purchase percentage (LPP). Under 100% LPP, all H_2 fuel bought within California is produced in California, while under the Default scenario a small portion is imported from outside the state. Thus, the 100% LPP scenarios are expected to generate slightly more jobs in California than the Default scenarios for the same level of fuel expenditures. Incorporating this LPP dimension creates four scenarios representing all possible combinations of the two variables: Base or High, Default or 100% LPP.

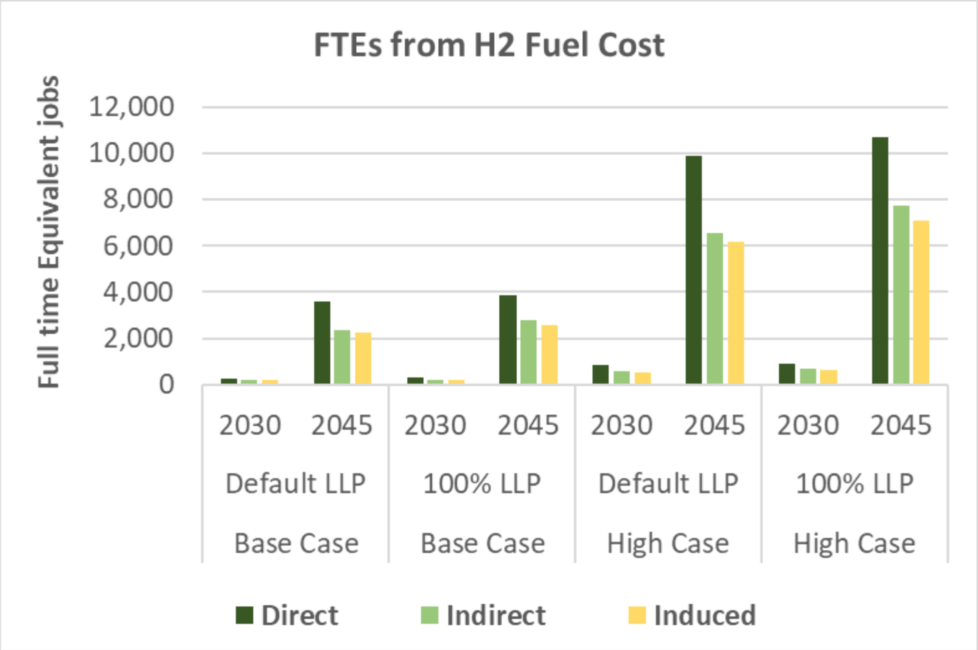

Figure 7. Job creation from expenditures on H_2 fuels, by job type, for scenarios differentiated by High Case vs. Base Case consumption and default vs. 100% LPP in 2030 and 2045.

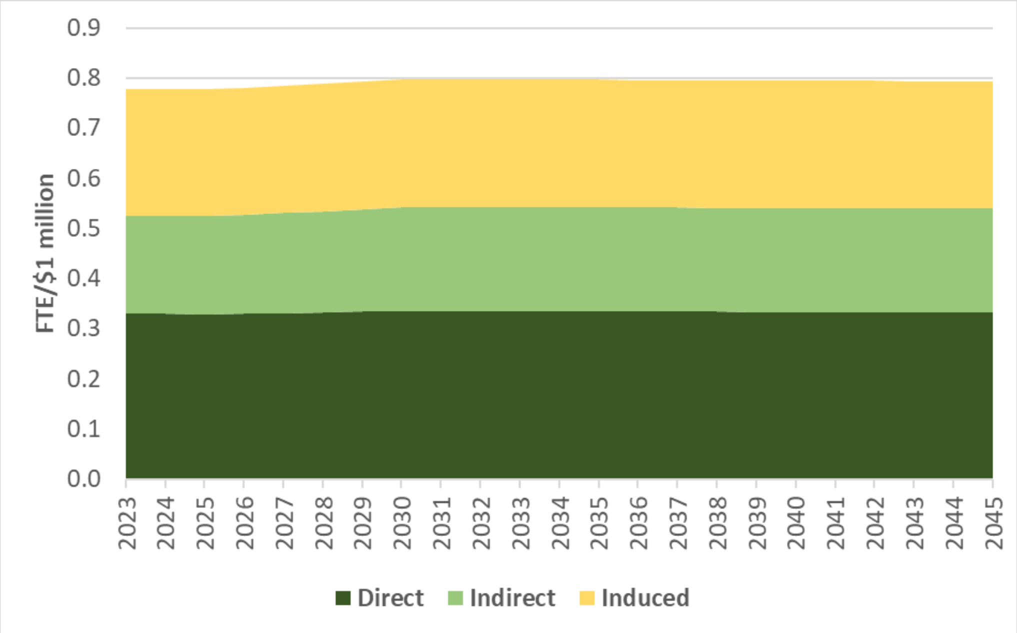

Figure 8. Modeled labor intensity of FCEV purchases by year from 2023 to 2045.

There is notable variation among the results of the four scenarios modeled. Fuel consumption is significantly greater under the two High Case scenarios when compared to the two Base Case scenarios. Labor intensity, measured in FTEs/$M, is slightly higher in the 100% local purchase percentage (LPP) scenarios versus the default LPP ones. Also of note is that labor intensity is slightly lower in 2045 than in 2023. This reflects economies of scale as the industry matures (Figure 8).

Direct vs. Indirect Jobs Created

Across all four scenarios, direct jobs make up a plurality of created jobs, followed by comparable numbers of indirect and induced jobs. The greatest absolute job growth is observed in the high fuel consumption 100% LPP scenario with a shift from close to 2,200 FTEs in 2030 to over 25,500 FTEs in 2045. A similar magnitude of growth—approximately a 20,700 increase in FTEs—is observed in the high fuel consumption default LPP scenario, while the base consumption scenarios see gains in the ballpark of 7,500 to 8,500 FTEs (Figure 7).

Examining the direct and indirect jobs created from fuels consumption, we see the greatest growth in occupations directly involved in hydrogen fuel transport, fuel generation, and provision of accompanying infrastructure (Table 9). The labor intensity of expenditures in this area exceeds that of occupations related to FCEV manufacturing. Three occupational areas – truck transportation; industrial gas manufacturing; and architectural, engineering, and related services – possess FTE/$M figures greater than the highest observed among occupations stemming from vehicle purchases. Jobs related to construction and maintenance of structures complete the top five direct occupations.

With indirect jobs, the model shows the greatest growth in administrative and managerial occupations, followed by occupations pertaining to goods transportation and vehicle maintenance. These gains are significantly lower in terms of labor intensity. All but the highest-growth occupation – employment services – generate an order of magnitude fewer FTEs per unit of expenditure than is the case with direct jobs.

Greater growth is expected among these occupations under the 100% LPP scenario than the default scenario as a portion of fuels expenditures that would otherwise support out-of-state jobs go toward California workers (Tables 9 and 10). However, these effects are not observed equally across occupations. LPP has no effect whatsoever on labor intensity for three of the top five direct growth occupations: infrastructure design, construction, and maintenance. Effects among indirect jobs, while non-zero, are muted. The greatest impact is seen in industrial gas manufacturing occupations, which rise in intensity from approximately 0.303 FTE/$M in the default scenario to 0.427 FTE/$M in the 100% LPP scenario – a 41% increase.

Table 9. Top five direct growth occupations from H_2 fuel expenditures, 100% and default LPP.

IMPLAN Occupation	NAICS Code(s)	FTE/$M
100% LPP		
1. Truck transportation	484	0.573
2. Industrial gas manufacturing	325120	0.427
3. Architectural, engineering, and related services	5413	0.360
4. Construction of new commercial structures, including farm structures	N/A*	0.165
5. Maintenance and repair construction of nonresidential structures	N/A*	0.0929
Default LPP		
1. Truck transportation	484	0.571
2. Architectural, engineering, and related services	5413	0.360
3. Industrial gas manufacturing	325120	0.303
4. Construction of new commercial structures, including farm structures	N/A*	0.165
5. Maintenance and repair construction of nonresidential structures	N/A*	0.0929

*Occupational areas specific to IMPLAN without a direct analogue in NAICS.

Table 10. Top five indirect growth occupations from H_2 fuel expenditures, 100% and default LPP.

IMPLAN Occupation	NAICS Code(s)	FTE/$M	
		100% LPP	*Default LPP*
1. Employment services	5613	0.119	0.109
2. Management of companies and enterprises	55111	0.0847	0.0656
3. Couriers and messengers	492	0.0605	0.0577
4. Truck transportation	484	0.0554	0.0455
5. Automotive repair and maintenance, except car washes	8111	0.0477	0.0428

Jobs Created by Construction

The highest-growth occupations for jobs pertaining to construction of H_2 refueling stations are architectural and engineering services for the 100% LPP scenario and employment services for the default LPP scenario (Table 11). Though the 10 top occupations generally align with jobs created in other sectors, the construction segment has the highest labor intensity values of any sector in this study. Architectural and engineering services jobs stand out in their level of growth at 1.41 FTE/$M. Demand for jobs related to construction and maintenance of structures are also quite high with approximately 0.66 and 0.37 FTE/$M, respectively. These figures suggest that the buildout of infrastructure for hydrogen fueling would be the greatest job creation source, per unit of investment, of any element covered in this study.

Table 11. Top five direct and indirect growth occupations from H_2 refueling station construction.

IMPLAN Occupation	NAICS Code	FTE/$M
Direct		
1. Architectural, engineering, and related services	5413	1.141
2. Construction of new commercial structures, including farm structures	N/A*	0.655
3. Maintenance and repair construction of nonresidential structures	N/A*	0.370
4. Truck transportation	484	0.0935
5. Other fabricated metal manufacturing	332999	0.0539
Indirect		
1. Employment services	5613	0.153
2. Other real estate	531	0.0539
3. Management consulting services	54161	0.0440
4. Retail – Building material and garden equipment and supplies stores	444	0.0426
5. Architectural, engineering, and related services	5413	0.0398

*Occupational areas specific to IMPLAN without a direct analogue in NAICS.

Job Quality and Equity Implications

Based on modeled growth within occupations and industries, we examine select metrics of job quality for the highest-growth areas to understand how beneficial these trends may be for California workers and where policy action can proactively address shortcomings. This analysis provides a high-level look at job quality for occupations with the greatest projected job growth. It also identifies opportunities for policymakers to create high-quality jobs and potential pathways to green jobs for fossil fuel workers.

This is not an exhaustive look at every occupation noted above, nor do we attempt to measure job quality in an empirical fashion. We do not model the geographic concentration of jobs and/or regional economic benefits thereof.

Among all the growth occupations identified above (Tables 8-11), we analyzed quality for jobs with a labor intensity over 0.1 FTE/$M. Generally, these were the highest-growth occupations:

1. Truck transportation
2. Industrial gas manufacturing
3. Architectural, engineering, and related services
4. All other miscellaneous electrical equipment and component manufacturing
5. Construction of new commercial structures, including farm structures
6. Maintenance and repair construction of nonresidential structures
7. Employment services

We use three metrics to characterize job quality across these seven occupations. The data for each metric varies in terms of its specificity to the occupation of interest and time frame:

1. **Annual wage** data from the BLS quarterly census of employment and wages is accessed using the Employment and Wages Data Viewer (USBLS 2024a). We use 2022 annual averages for private sector industries for the NAICS code of interest. Results are filtered by California counties. We calculate average annual wages per employee across all California counties for which data are provided, weighted by annual average employment for each county.
2. **Healthcare benefit access** data are available at the industry level from the BLS National Compensation Survey: Employee Benefits in the United States, March 2022 (USBLS 2022a). As indicated in the title, this is a national dataset. It does not capture how conditions in California may vary from the national average. We use the figure for “Access” within “Incidence of healthcare benefits for private industries” within which the occupations of interest fall.
3. **Workforce percentage represented by a union** data are taken from the BLS January 2023 economic news release, Table 3: Union affiliation of employed wage and salary workers by occupation and industry, 2022-2023 annual averages (USBLS 2023). We use the 2022 “percent of employed” figure for workers represented by unions (as opposed to members of unions) for the occupation or industry within which our occupations of interest fall. The 2022 figure was most the most recent data available at the time of writing; BLS has since updated this source with data for 2023.

The selected metrics for the six highest growth occupations paint a generally positive picture (Table 12, Table 13). Apart from construction and employment services jobs, access to healthcare benefits is high in the occupations where we anticipate the greatest growth, and unionization rates range from a lower bound on par with the current national average of 6% for all industries in 2022 (Statista Research

Department 2024) to well above. Wages appear healthy among the more technical sectors and construction. The potential for clean hydrogen production to create an ongoing source of well-paying, green gas manufacturing jobs is especially promising because it has just transition implications. Should production infrastructure be sited in regions where the fossil gas industry has been previously active, there is the potential for clean hydrogen to provide a new source of employment. This would create opportunities for workers with preexisting skillsets in communities that have historically been environmentally burdened by fossil industry activities to enter the clean energy sector.

Table 12. Job quality metrics for the six highest-growth occupations, 2022 to 2023.

IMPLAN Occupation	NAICS Code	*California, NAICS-level*	*National, Industry/Occupation Group-Level*	
		Annual Wages (USD)	Access to Healthcare Benefits** (% of industry workers)	Representation by Unions** (% of employed)
Truck transportation	484	$63,116	85%	15.5%
Industrial gas manufacturing	325120	$120,417	90%	8.1%
Architectural, engineering, and related services	5413	$121,905	89%	6.9%
All other miscellaneous electrical equipment and component manufacturing	335999	$86,077	90%	8.9%
Construction of new commercial structures, including farm structures	2362*	$107,739	75%	12.4%
Maintenance and repair construction of nonresidential structures	2362*	$107,739	79%	10.5%
Employment services	5613	$59,563	54%	9.5%

*Because the IMPLAN occupation does not have a direct NAICS analogue, we utilize NAICS 2362: nonresidential building construction as an approximate match for calculating wage data.

**For clarification on which industries healthcare access and union representation data is derived from, see Table 13.

Table 13. Industry and occupation data-matching for healthcare benefit access and union representation figures (USBLS 2022b, 2023).

IMPLAN Occupation	Healthcare Benefit Access Classification*	Union Representation Classification**
Truck transportation	Trade, transportation, and utilities → Transportation and warehousing	Nonagricultural industries → Transportation and utilities → Transportation and warehousing
Industrial gas manufacturing	Goods-producing industries → Manufacturing	Nonagricultural industries → Manufacturing → Nondurable goods
Architectural, engineering, and related services	Service-providing industries → Professional and business services → Professional and technical services	Management, professional, and related occupations → Professional and related occupations → Architecture and engineering occupations
All other miscellaneous electrical equipment and component manufacturing	Goods-producing industries → Manufacturing	Nonagricultural industries → Manufacturing → Durable goods
Construction of new commercial structures, including farm structures	Goods-producing industries → Construction	Nonagricultural industries → Construction
Maintenance and repair construction of nonresidential structures	(Occupational group) Natural resources, construction, and maintenance → Installation, maintenance, and repair	Service occupations → Building and grounds cleaning and maintenance occupations
Employment services	Service-providing industries → Professional and business services → Administrative and waste services	Sales and office occupations → Office and administrative support occupations

* USBLS 2022b

** USBLS 2023

However, the generally positive picture for job quality is complicated by the fact that jobs within these NAICS codes are not monolithic, and wages and access to benefits may vary worker to worker. In some occupations of interest, specific types of workers that make up large portions of the workforce may have wages that fall significantly below the occupational average. For instance, when examining national numbers from BLS Occupational Employment and Wage Statistics May 2022 dataset (USBLS 2024b):

- The single-largest sub-sector of employment services workers – transportation and material moving occupations – have an annual mean wage of $33,630 compared to a mean of $50,910 across the sector.
- Construction trades workers, which compose almost 40% nonresidential building construction jobs nationally, have an annual mean wage approximately $13,000 lower than the nonresidential building construction industry average ($63,980 versus $77,160).
- Assemblers and fabricators – composing 31.1% of employment in the “other electrical equipment and component manufacturing” industry – make approximately 2/3 of the industry’s average wage ($39,150 vs. $60,850).

The decades-long decline of organized labor in the United States — due in part to the role of government in empowering businesses over workers — means that simply meeting or exceeding the national rate for union membership is an insufficient measure of success. Per the Organisation for Economic Co-operation and Development (OECD), the US ranked well behind many other developed economies in trade union density as of 2019. At that time, the US national rate of 9.9% was on par with nations such as Turkey and Lithuania (OECD 2024). Union membership rates in the US were less than half that of peer countries like the United Kingdom and were well behind global leaders like Denmark (67%) and Iceland (91.4%) (McEvoy 2024).

These numbers do not capture the negative effects on many workers from adverse working conditions and business practices. These can include unsafe or abusive working environments and exploitative business practices. Examples include (1) alleged racist practices against Black Tesla workers that prompted the State of California to file a lawsuit against the firm and (2) employment misclassification and the saddling of workers with business expenses by the trucking industry (Roosevelt and Mitchell 2022; Murphy 2017).

General strategies we recommend to legislators, policymakers, and regulators working on California’s hydrogen buildout are:

- Leverage California’s purchasing power to improve job quality and equitable job access through measures such as funding eligibility and contract requirements. Private actors seeking state funds or contracts can be required to meet minimum standards for workers, including unionization, benefits, and local and diversity hiring provisions. ARCHES is requiring such standards in the statewide hydrogen hub it is pursuing.
- Provide robust support for organized labor as the clean hydrogen industry and its supply chains are developed. Unionization increases wages and enables workers to negotiate with industry to address workplace-specific issues such as unsafe working conditions. With the State Building and Construction Trades Council of California as a founding partner, ARCHES can serve as a model.
- Support and facilitate programs to transition fossil industry workers with specialized, transferable skills into new, green jobs in the clean hydrogen sector. Site elements of the clean hydrogen industry in communities that have been historically burdened by fossil fuel industry

activities. ARCHES has included these principles in its winning proposal to the US Department of Energy and can serve as a learning laboratory for implementing them.

A point-by-point plan to address these issues is outside the scope of our current analysis. This would be helpful to explore as plans for a hydrogen fueling system become more concrete.

References

ANL (2024), Argonne National Laboratory hydrogen station models (HDSAM, HRSAM, HDRSAM) and documentation reports, https://www.hdsam.es.anl.gov

ARCHES (2024), California Alliance for Renewable, Clean Hydrogen Energy Systems, ARCHES website, https://archesh2.org

Baker, Sarah E. et al. (2020). *Getting to Neutral: Options for Negative Carbon Emissions in California*, January, 2020, Lawrence Livermore National Laboratory, LLNL-TR-796100 https://www-gs.llnl.gov/content/assets/docs/energy/Getting_to_Neutral.pdf

Brown, Austin L. et al. (2021). *Driving California's Transportation Emissions to Zero*. UC Office of the President: University of California Institute of Transportation Studies. http://dx.doi.org/10.7922/G2MC8X9X. Retrieved from https://escholarship.org/uc/item/3np3p2t0

CARB (2021). *Hydrogen Station Network Self-Sufficiency Analysis* per Assembly Bill 8, October 2021, https://ww2.arb.ca.gov/sites/default/files/2021-10/hydrogen_self_sufficiency_report.pdf

CARB (2022a). Scoping Plan Documents, including *Final 2022 Scoping Plan Update and Appendices*. https://ww2.arb.ca.gov/our-work/programs/ab-32-climate-change-scoping-plan/2022-scoping-plan-documents#:~:text=The%202022%20Scoping%20Plan%20Update%20focuses%20on%20outcomes%20needed%20to,economic%2C%20environmental%2C%20energy%20security%2C

CARB (2022b). *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development* (Report Pursuant to Assembly Bill 8; Perea, Chapter 401, Statutes of 2013), https://ww2.arb.ca.gov/sites/default/files/2022-09/AB-8-Report-2022-Final.pdf

CEC, CARB (2022). Joint Agency Staff Report on Assembly Bill 8: 2022 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California, California Energy Commission and Air Resources Board https://www.energy.ca.gov/sites/default/files/2022-12/CEC-600-2022-064.pdf

Cochran, Jaquelin *et al*. (2021). *The Los Angeles 100% Renewable Energy Study (LA 100)*. https://www.nrel.gov/analysis/los-angeles-100-percent-renewable-study.html

Coffee, Daniel et al. (2022). *Workforce Impacts of Achieving Carbon-Neutral Transportation in California*. Regents of the University of California, Los Angeles. https://innovation.luskin.ucla.edu/wp-content/uploads/2022/09/Workforce-Impacts-of-Achieving-Carbon-Neutral-Transportation-in-California.pdf.

DOE (2023), Description of Hydrogen Hubs program, https://www.energy.gov/oced/regional-clean-hydrogen-hubs-0

DOE (2021). "Hydrogen Shot" program description and goals, and related materials web page, https://www.energy.gov/eere/fuelcells/hydrogen-shot

E3 (2020). Achieving Carbon Neutrality in California: Pathways Scenarios Developed for the *California Air Resources Board*, Energy and Environmental Economics, October 2020. https://ww2.arb.ca.gov/sites/default/files/2020-10/e3_cn_final_report_oct2020_0.pdf

FCHEA (2020). *Road Map to a US Hydrogen Economy, Reducing Emissions and Driving Growth Across the Nation*, (20+ authoring organizations under the Fuel Cell & Hydrogen Energy Association umbrella), https://static1.squarespace.com/static/53ab1feee4b0bef0179a1563/t/5e7ca9d6c8fb3629d399fe0c/1585228263363/Road+Map+to+a+US+Hydrogen+Economy+Full+Report.pdf.

Fulton, L. et al. (2023). California Hydrogen Analysis Project: The Future Role of Hydrogen in a Carbon-Neutral California: Final Synthesis Modeling Report. UC Davis: Hydrogen Pathways Program. UC Davis Institute of Transportation Studies. https://escholarship.org/uc/item/27m7g841

Hydrogen Council (2021). *Hydrogen Insights*. https://hydrogencouncil.com/wp-content/uploads/2021/02/Hydrogen-Insights-2021.pdf

Hydrogen Council (2020). *Path to hydrogen competitiveness: A cost perspective*. Prepared for the Hydrogen Council by McKinsey. https://hydrogencouncil.com/en/path-to-hydrogen-competitiveness-a-cost-perspective.

IEA (2022). *Global Hydrogen Review*, International Energy Agency, Paris. https://www.iea.org/reports/global-hydrogen-review-2022

IEA (2019). *The Future of Hydrogen: Seizing Today's Opportunities*, Report prepared by the IEA for the G20, Japan. International Energy Agency, OECD Paris. https://www.iea.org/reports/the-future-of-hydrogen

IMPLAN (2022). California State Total data package and software. IMPLAN® Group LLC, Huntersville, NC. https://implan.com/

ITS-Davis (2024). Hydrogen and Fuel Cell Vehicle Projects (web page). University of California, Davis, Institute of Transportation Studies. https://its.ucdavis.edu/research/uc-davis-hydrogen-fuel-cell-projects/

McEvoy (2024). *Countries with the highest percentage share of their workforce being members of labor unions worldwide as of 2020*. Survey 2008-2020. https://www.statista.com/statistics/1356735/labor-unions-most-unionized-countries-worldwide/

Murphy, Brett (2017). *Retail giants enable trucker exploitation*. USA Today. Accessed Sep 22, 2023. https://www.usatoday.com/pages/interactives/news/rigged-retail-giants-enable-trucker-exploitation/

NREL (2019). SERA Scenario Evaluation and Regionalization Analysis Model, model home page and links to specific reports (reference date used here based on date of most recent report), https://www.nrel.gov/hydrogen/sera-model.html

NREL (2020). H2@Scale report: Ruth, Mark, Paige Jadun, Nicholas Gilroy, Elizabeth Connelly, Richard Boardman, A.J. Simon, Amgad Elgowainy, and Jarett Zuboy. 2020. *The Technical and Economic Potential of the H2@Scale Concept within the United States*. Golden, CO: National Renewable Energy Laboratory. NREL/TP- 6A20-77610. https://www.nrel.gov/docs/fy21osti/77610.pdf

Organisation for Economic Co-operation and Development (2024). Trade Union Dataset. https://stats.oecd.org/Index.aspx?DataSetCode=TUD

Reed, Jeffrey et al. (2020). *Roadmap for the Deployment and Buildout of Renewable Hydrogen Production Plants in California*. Prepared by UC Irvine for California Energy Commission. Publication Number: CEC-600-2020-002. https://cafcp.org/sites/default/files/Roadmap-for-Deployment-and-Buildout-of-RH2-UCI-CEC-June-2020.pdf

Roosevelt, Margot & Russ Mitchell (2022). *Horrific allegations of racism prompt California lawsuit against Tesla*. Los Angeles Times. Accessed Sep 22, 2023. https://www.latimes.com/business/story/2022-02-11/la-fi-tesla-race-discrimination-lawsuit

Statista Research Department (2024). Rate of union membership in the manufacturing industry in the United States from 2000 to 2023. https://www.statista.com/statistics/1376233/union-membership-rate-manufacturing-industry-us/

US Department of Labor, Bureau of Labor Statistics (2022a). *National Compensation Survey: Employee Benefits in the United States*. March 2022. https://www.bls.gov/ebs/publications/september-2022-landing-page-employee-benefits-in-the-united-states-march-2022.htm

US Department of Labor, Bureau of Labor Statistics (2022b). *Table 4. Private industry workers by industry group or occupational group*. Economic news release, December 2023. https://www.bls.gov/news.release/ecec.t04.htm

US Department of Labor, Bureau of Labor Statistics (2023). *Table 3: Union affiliation of employed wage and salary workers by occupation and industry*. 2021-2022 annual averages. Economic news release, January 2023. https://www.bls.gov/news.release/union2.t03.htm

US Department of Labor Bureau of Labor Statistics (2024a). Quarterly Census of Employment and Wages (Data Viewer). 2022 annual averages for private sector industries. https://data.bls.gov/cew/apps/data_views/data_views.htm#tab=Tables

US Department of Labor, Bureau of Labor Statistics (2024b). *May 2023 National Industry-Specific Occupational Employment and Wage Estimates*. Occupational Employment and Wage Statistics. https://www.bls.gov/oes/current/oessrci.htm

Vijayakumar, V., A Jenn, L. Fulton (2021). *Low Carbon Scenario Analysis of a Hydrogen-Based Energy Transition for On-Road Transportation in California*. Energies. 14 (21), 7163. https://www.mdpi.com/1996-1073/14/21/7163

White House (2023), Hydrogen Hubs Announcement, https://www.whitehouse.gov/briefing-room/statements-releases/2023/10/13/biden-harris-administration-announces-regional-clean-hydrogen-hubs-to-drive-clean-manufacturing-and-jobs/#:~:text=President%20Biden's%20Bipartisan%20Infrastructure%20Law,delivery%2C%2

Yang, Chris and Joan Ogden (2007). *Determining the lowest-cost hydrogen delivery mode*. International Journal of Hydrogen Energy. 32 (2), pp 268-286. https://www.sciencedirect.com/science/article/pii/S0360319906001765