Title

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Authors

Fulton, Lewis
UC Davis ITS Hydrogen Study Team

Publication Date

2024-04-01

DOI

10.7922/G27W69K2

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Hydrogen Modeling Report

Lewis Fulton and UC Davis ITS Hydrogen Study Team

April 26, 2024

UC DAVIS
Institute of Transportation Studies

DOI: 10.7922/G27W69K2

UCD-ITS-RR-24-27

Acknowledgements

UC Davis Hydrogen Team members who provided input to this report include Chris Yang, Stefania Mitova, and Marshall Miller. The authors would like to thank the UC Davis Sustainable Transportation Energy Pathways (STEPS) Energy Futures Program sponsors for funding support. They would also like to thank the following reviewers for their comments and suggestions: Diane Moss, Renewables 100 Policy Institute; Andrew Martinez, California Air Resources Board; Vijai Atavane, SoCalGas; and reviewers from the Hydrogen Fuel Cell Partnership (H2FCP), Volvo Group, US EPA, and American Honda Motor Corp.

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Executive Summary

This paper reports on scenarios (a Base Case and High Case) for the uptake of fuel-cell electric vehicles (FCEVs) in California, including light-duty vehicles (LDVs), medium-duty vehicles (MDVs) and heavy-duty vehicles (HDVs), projected to 2030 and out to 2050. These scenarios may be best thought of as providing potential targets and pathways for FCEV adoption, but are not predictions and are by no means assured. Our Base Case reaches 120k LDVs, 9k MDVs, and 4k HDVs by 2030. Our High Case reaches about twice these numbers. Vehicle numbers continue to increase after 2030, and reach almost a factor of 10 times the 2030 levels in 2050.

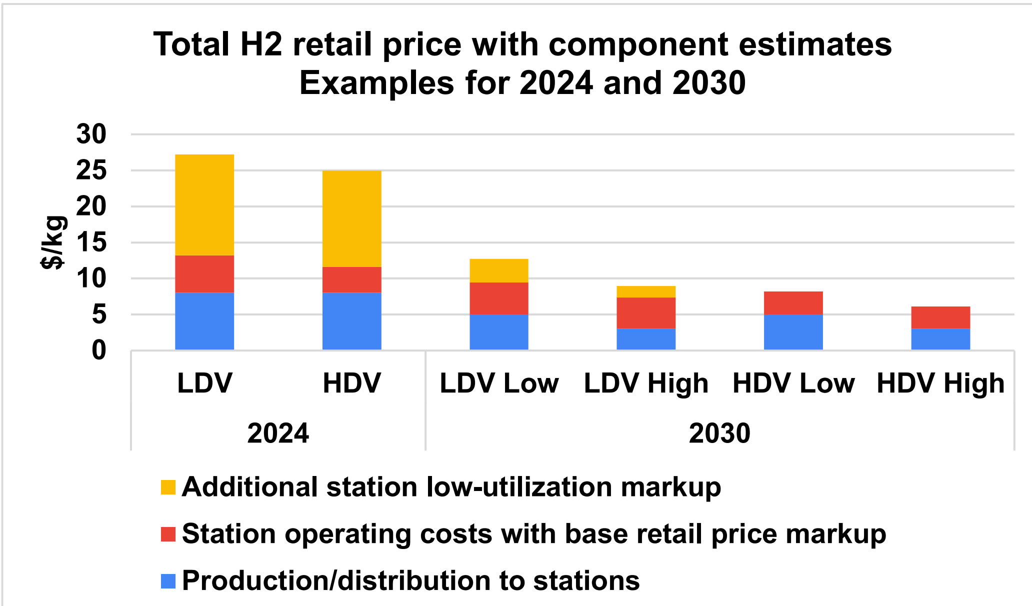
This analysis then uses the scenarios for FCEV sales and stocks to estimate the need for stations that will refuel those vehicles, with a particular focus on station economics. We create scenarios with enough light- and medium-duty vehicle (LMDV) refueling stations (assuming all new LDV stations can also refuel MDVs), and separately enough HDV stations, with enough overall station capacity to easily refuel the relevant vehicles for their on-road energy requirements. In addition, we rapidly increase the number of stations to 2030, to achieve geographic coverage, that appear likely to be adequate for convenient refueling options around the state (175 stations for LMDVs, 50 for HDVs). After these station numbers are reached, we add stations as needed, based on vehicle sales and hydrogen demand growth.

Given our vehicle sales and station scenarios considered, we find:

- Current LMDV hydrogen refueling stations in California are, on average, utilized with an average rate of around 20% of potential capacity. With rapid station growth to 2030, and given the LMDV sales and stock projections in our Base Case, we estimate that this low-utilization situation will continue until at least 2030, resulting in challenging economics for those stations and/or potentially high retail hydrogen prices.
- We find that a rollout of heavy duty trucks, with dedicated stations, given ARCHES' (California hydrogen hub) expected targets of 5000 trucks and 50 stations by 2031, would result in some underutilization but much less than in the LMDV scenario. HDV stations would experience lower losses and faster achievement of breakeven points, due both to inherent cost advantages for these HDV stations, and the fact that HDVs use far more hydrogen per day than light or medium duty vehicles, resulting in faster overall hydrogen demand growth relative to station growth.
- In our High Case (with faster vehicle sales than the Base Case, but the same rate of station additions to 2030) there are significantly lower losses to both LMDV and HDV stations than in the Base Case, and breakeven points are hit several years earlier.
- We consider station price markups to hydrogen sold to vehicles, including a "base" markup which we define as that which achieves normal economic returns with an 80% utilization rate (average hydrogen sales at 80% of capacity). We estimate these to be in the range of \$2.50 to \$4.00 per kg sold to vehicles, above the price paid for hydrogen production and delivery to the station.
- We also estimate an additional "low-utilization" station price markup that would be needed to prevent losses with lower utilization rates. In our scenarios, in 2025 stations may average as low as 20% utilization rates; at this level, the additional markup to cover costs would be around \$13-15/kg. Such high markups would decline as sales rise over time, with a growing market. These are shown in Figure ES-1, along with the base markup (at 80% utilization) and a range of \$5-8/kg for hydrogen

production and distribution to the station. Stations could only charge these additional markups if they are price setters rather than price takers; if not, they would simply lose money during periods of low utilization.

Figure ES-1. Hydrogen retail prices including additional station price markups for low utilization



- Such high markups can help explain high retail hydrogen prices during this period; given a production and delivery hydrogen cost range of \$5-8/kg, a base station markup of \$2.5-4, and a temporary (low utilization) additional markup of \$14, the final (pre-tax/subsidy) price to the consumer would be in the range of \$21 to \$26/kg. Other factors, such as restricted hydrogen supply, or higher than anticipated station operation and maintenance costs, could send prices even higher.
- The low-utilization markups will decline over time with improved utilization; this means that the faster the growth in vehicles and hydrogen demand, the faster the stations will reach breakeven points and eliminate excess markups. For LMDVs, this can also be achieved to some degree by limiting the number of stations built by 2030 to something below 175; we include a 100 station case in our sensitivity analysis that helps reduce the time to reach a breakeven point. But more research is needed to understand the minimum number of stations needed to provide adequate geographic coverage around the state.

Overall, the results suggest that until station utilization is high, cost burdens represent a “valley of death” situation that can lead to very high H2 prices and/or station financial failures. Economic incentives and market spurring measures to ensure station operators can survive this period will be critical, with this period potentially lasting until at least the late 2020s and potentially into the early 2030s. The period can be shortened with faster and higher sales levels and hydrogen demand; it can also be improved by building fewer stations, but then there is a risk that there won’t be sufficient geographic coverage to meet drivers’ and fleets’ mobility needs.

This report does not assess policies that could be (or are being) used to address station cost and profitability issues; these will be addressed in a follow-up paper. Policies may be needed to address very high costs per kg over the next few years; Existing policies such as the Low-carbon Fuel Standard (LCFS) can help, but may not be sufficient in this situation. Other policies could include market development measures such as financing or direct funding for stations, further hydrogen price incentives and other fiscal measures, and market growth oriented measures, such as fuel cell vehicle sales incentives.

Introduction

California is committed to developing a large-scale hydrogen system over the next decade (ARCHES, 2024) and as a key part of this endeavor, expects road transportation vehicles to become an important source of hydrogen demand. This aligns with the state goal to rapidly transition to zero-emission vehicles, as required by the Advanced Clean Cars II, Advanced Clean Trucks, Advanced Clean Fleets, and Innovative Clean Transit programs. Achieving these aims will necessitate rapid yet efficient infrastructure rollout to support vehicle refueling.

This report considers how to build out public hydrogen refueling stations in California for both LMDVs and separately for HDVs in a manner that maximizes hydrogen station coverage while minimizing cost. It also estimates extra costs and profit losses to stations builders/operators during the initial station development period, when hydrogen demand will remain lower than needed for all operating stations to make an adequate return on investment.

This analysis is part of our broader, on-going UC Davis study, *California Hydrogen Analysis Project*, and uses scenarios slightly modified from those originally presented in detail in our *Final Synthesis Modeling Report* (UCD/H2, 2023). In line with that document, we consider scenarios for the rollout of tens of thousands of FCEV cars, trucks and buses, taking into account California ZEV policies and plans for massive investments in hydrogen and FCEV related infrastructure.

In this current document, we specifically consider the implications for a Base Case and High Case for vehicle sales on station requirements. This includes projecting vehicle sales, stocks, travel and hydrogen demand around the state. We use a spatial travel model (STIEVE, described in UCD/H2 2023) to allocate hydrogen demand in some detail and estimate the number and sizes of stations needed to meet that demand, with a minimal deviation from vehicles' planned routes. Such routes cannot be achieved in early days with few stations, but stations can be added in a manner that provides maximum benefit to the most vehicles. We roll out a system that appears sufficient to provide adequate refueling around the state with minimum travel deviations by 2030. This rollout is also consistent with California state, and ARCHES hydrogen hub, planning and targets.

We consider stations for LDVs and MDVs together, as we assume they can both refuel at the same type of stations with equipment sized to suit all the different vehicle classes up through Class 6. We thus term these as LMDV stations. However we note that currently most LDV hydrogen stations are not able to serve MDVs, a situation that should change with station expansion. We assume HDVs refuel at different stations from LMDVs, with spacing and station sizing that can accommodate 18 wheelers, along with hydrogen storage and refueling technology (such as fast refill) designed for large capacity on-board tank systems. We note, however, that it should be possible to construct HDV stations that can also provide fuel for LMDVs, such as is often currently done with gasoline/diesel refueling stations along highways. This is not directly addressed in this paper but could be an important way to increase LMDV station coverage when building HDV stations.

The scope of this report does not include consideration of specific station technologies, but we have covered these topics elsewhere. Furthermore, we do not consider various station constraints, such as refueling limits per hour, total nozzle availability, or other factors that might cause the daily refueling of vehicles to be less than the rated capacity of the station. We additionally assume that a fully utilized station is operating at 80% of its rated capacity and consider how this relates to the number of vehicles on the road that will need to regularly refuel.

Hydrogen Refueling Station Buildout Plans to 2030

California has developed plans to build out hydrogen refueling stations to at least 2030. The following is a summary of key information and status reports from the California Air Resources Board (ARB), the California Energy Commission (CEC), and the Hydrogen Fuel Cell Partnership (H2FCP, formerly CAFCP) related to these plans and station status. This information is consistent with that received in direct communication with the CEC about station funding and planned rollout. The implications for stations and vehicles for recent and future years can be summarized as follows:

California station rollout status and future projections:

Status in 2024: As of April 2024, H2FCP tracking shows 55 light-duty hydrogen stations operational, with 6 others unavailable, 2 in construction, 18 in permitting, 5 on hold, and 4 others proposed (funded with site control), for a total of 90 open and planned retail stations. This may not include all potential or planned stations, since not all may be reported to H2FCP. Also, while no HDV-dedicated stations have been opened as of April 2024, according to H2FCP website, 3 current stations can accommodate HDVs, and 9 funded stations will be able to.

State plans: In their 2022 *Annual Evaluation of Fuel Cell Electric Vehicle Deployment and Hydrogen Fuel Station Network Development* (CARB 2022), CARB projected that 98 stations would be open by the end of 2023, which according to H2FCP tracking cited above, is significantly delayed. Executive Order B-48-18 called for installation of 200 hydrogen refueling stations by 2025, although CARB shows the number of stations topping out with current funding streams at 176 by 2028, and the CEC's and CARB's *Joint Agency Staff Report on Assembly Bill 8: 2022 Annual Assessment of Time and Cost Needed to Attain 100 Hydrogen Refueling Stations in California* (CEC, 2002) indicates known plans and funding for 175 stations.

Overall there are about 55-60 stations operating in the state, with another 30-35 stations in active planning or development, and additional known plans leading to 175 total. We note that in recent years, at least through Spring 2023, stations in all regions of California were generally utilized at around 20% of their capacity (CEC, 2023). This means that they were only serving about 1/5 the numbers of vehicles they have the capacity to serve. As the CEC 2023 report shows, the utilization rate does vary substantially in specific areas, and from month to month, and there are some places and times where there may even be a shortage of station capacity, such as when some stations are out of service, or there is a shortage of hydrogen supply, or other short-term reasons. In this study, we focus on annual state-wide averages and assume that we start at 20% utilization rate. This is also consistent with the numbers and capacity of stations, and numbers of vehicles in operation, as of 2024.

Based on this information, it seems reasonable to project that 150-200 stations could be built by 2030, but this will require that the state is committed to achieving this number through various funding and incentive programs. Otherwise, the number of stations could remain below 100.

FCEV Growth and Station Buildout Scenarios

As reported in UCD/H2 (2023), we created a set of scenarios (Base and High Case) for light-, medium- and heavy-duty FCEVs, including sales, stocks, daily travel, and daily hydrogen demand. We used these scenarios to inform our California spatial model (STIEVE) and create a map showing how hydrogen would grow and where refueling demand would be. This helped form the basis for understanding the need for stations, taking into account not only hydrogen demand, but also the need for station coverage around the state that enables vehicles to travel to all major destinations and be able to find fuel to continue trips. Stations, in turn, must have enough daily capacity to meet average and peak demands, particularly to serve dense areas and major highways where most refueling is likely to occur. Our UCD/H2 (2023) modeling report explains the logic of this effort in detail, while this current document is limited to presenting information on hydrogen demand and the size and number of stations needed.

We note that ARB has considered the growth in LDVs along with stations (ARB 2022) and projected, based on OEM production plans, that in 2028, the number of LDVs will only utilize about 30% of the capacity that the projected number of stations at that time could serve. Thus, there would be an average 30% utilization, which suggests poor economic returns for operating the stations. This means either that stations would increase their price markup for each kg of hydrogen sold, to avoid losing money, or else lose money, if they can't do this (e.g. if they are "price takers" rather than "price setters" in the market).

ARB also notes that the manufacturers indicate their plans are affected by relatively poor recent station performance (lack of reliability or available hydrogen), and that if these metrics improve, growth in the number of vehicles sold could be much higher than these projections. Our research does not attempt to factor in recent station technical and reliability performance and basically assumes that in the future, stations will perform reasonably well.

Further, as described in UCD/H2 (2023), our vehicle sales and stock projections are simply scenarios meant to motivate comparisons to needed stations, to understand the extent to which excess station capacity may occur and what it may cost. These scenarios are probably dependent on achieving competitive FCEV and H2 prices, though this could include the use of policies such as price incentives to achieve something close to cost parity with gasoline or diesel fuel. As shown in this paper, as the market for H2 vehicles and fuels grows, costs and prices should drop, allowing incentive policies to eventually be phased out. But the growth of the market will depend in part on having sufficient numbers of refueling stations in place to spur consumer demand for vehicles and ensure they can find fuel in most population centers and travel routes around the state.

Our FCEV stock projections by major vehicle type, for the Base and High Case, are shown in Table 1 for selected years. Heavy-duty trucks are separated into long haul (300+ miles/day) and short haul/drayage applications. Vocations vehicles are not included in this table. These stock numbers reflect our assumptions on sales shares (not shown) and stock turnover rates. In general, we assume a low sales share for FC light-duty vehicles about 4% in 2030 in the Base Case and 8% in the High Case. HDVs have a much higher share, with 50% or more for long haul in the Base Case and 75% in the High Case after 2030. LD FCEVs reach nearly 2 million by 2050 in the Base Case and over 5 million in the High Case, relative to a total California light-duty vehicle stock of around 40 million in that year. Thus, LD FCEVs are not a high share of total stock but amount to a large number of vehicles, nonetheless. HD FCEVs, including long haul, short haul and drayage, all are projected to account for larger shares, specifically 30-50% of total California truck stock in 2050 in the Base Case and 50-75% in the High Case.

Table 1. Base and High Case scenario FCEV stock by vehicle type (thousands), selected years

		2023	2025	2027	2030	2035	2040	2045	2050
Base Case									
	LDVs	15	18	31	118	427	853	1,318	1,660
	MDVs	0.0	0.2	1.9	8.6	39	113	205	274
	HDV Long haul	0.0	0.1	0.7	3.2	11.7	28	44	54
	HDV Short Haul/Dray	0.0	0.0	0.2	0.9	3.5	8	12	15
	Transit Buses	0.0	0.2	0.5	1.3	2.9	5	6	6
High Case									
	LDVs	15	21	55	243	1,066	2,274	3,528	4,813
	MDVs	0.0	0.4	5.3	20	83	238	430	572
	HDV Long haul	0.0	0.1	1.1	5.3	21	54	92	117
	HDV Short Haul/Dray	0.0	0.0	0.3	1.4	5.9	15	24	30
	Transit Buses	0.0	0.2	0.8	2.3	5.2	8	9	10

While LDVs dominate projected FCEV sales in terms of stock numbers, they use relatively little hydrogen per vehicle (estimated to be around 0.7 kg/day/vehicle on average), while HDVs use much more (around 40kg/day on average in moderately long-haul trucks). The resulting total hydrogen demand by vehicle type through 2050 for the Base and High demand cases are shown in Table 2 and Figure 1, which presents a more detailed breakout by vehicle type. As shown in both, the Base Case hydrogen demand reaches about 6 tons/day by 2050 and 14 tons/day in 2050 in the High Case.

Figure 1. Hydrogen demand by vehicle type, Base and High Case, through 2050

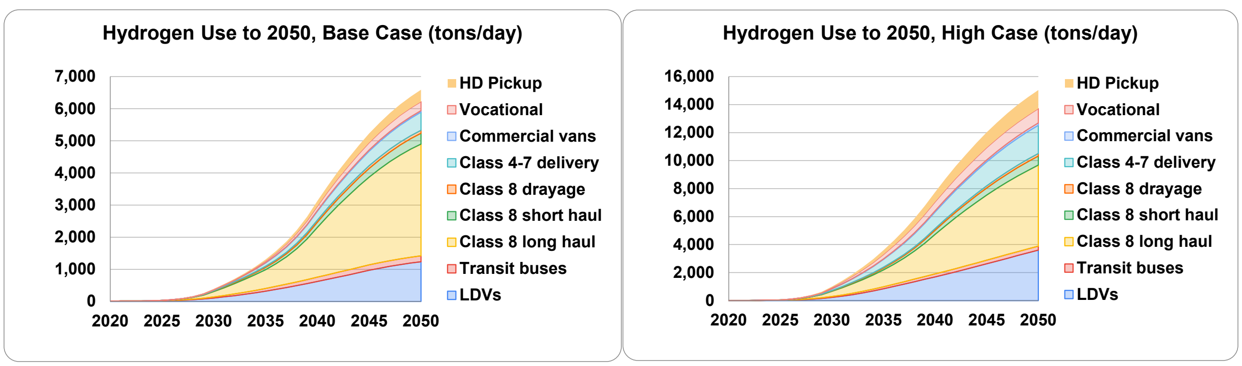


Table 2. Hydrogen demand (tons/day) by vehicle type and scenario, selected years

		2023	2025	2027	2030	2035	2040	2045	2050
Base Case									
	LDVs	10	12	22	83	298	596	921	1,159
	MDVs	0	1	9	44	204	572	1,005	1,313
	HDV Long haul	0	4	44	210	769	1,829	2,916	3,606
	HDV Short Haul/Dray:	0	0	2	6	25	47	62	69
	Transit Buses	1	4	12	31	69	108	138	153
	Total	12	22	88	374	1,365	3,153	5,040	6,301
High Case									
	LDVs	10	14	39	170	745	1,589	2,465	3,363
	MDVs	0	2	30	111	459	1,275	2,207	2,868
	HDV Long haul	0	7	73	345	1,354	3,550	6,034	7,701
	HDV Short Haul/Dray:	0	0	2	10	41	84	116	134
	Transit Buses	1	5	19	55	125	184	226	249
	Total	12	29	162	691	2,725	6,682	11,048	14,314

To match these hydrogen demand scenarios, we created comparable Base and High Case station buildout scenarios through 2050, linked to our spatial analysis of refueling and with particular attention to the growth of stations through 2035. As mentioned, the number of stations built has to meet minimum locational requirements, which our modeling suggests are roughly in the 100-150 station range for LDVs and MDVs (meaning stations that can serve both, or LMDV stations), by 2030, and in the 50-75 station range for HDVs. In the Base vs the High case, in order to meet the hydrogen demand (as shown in Table 2), the numbers of stations needed are identical through 2027 and still close in 2030. By 2035, most station growth is tied to keeping up with the specific demand in this scenario. The High Case requires increasingly greater numbers of stations than the Base Case, and the difference between the two scenarios eventually exceeds one hundred stations for both the LMDV and HDVs.

It should also be noted that new stations are built at a minimum size until an 80% utilization rate is reached, then increased over time, in order to accommodate more vehicles per day and help cut costs per station. The HDV stations are considerably bigger in all years than the LMDV stations, given the high refueling requirements per vehicle served. The HDV station capacity for new stations in 2023 is assumed to be 4 tons/day, while only 1.5 tons/day for LMDV stations. These estimates are based on recent examples and discussions with station builders about expected plans.

Table 3. Numbers and sizes of stations in service by vehicle type and scenario, by year

		2023	2025	2027	2030	2035	2040	2045	2050
Base Case									
Station numbers	L/MDV	60	73	100	175	255	427	602	732
	HDV	2	10	26	56	133	262	415	513
New station capacities (t/day)	L/MDV	1.5	1.5	1.5	1.5	2.0	2.5	2.5	2.5
	HDV	4.0	4.0	4.0	5.0	10.0	10.0	10.0	10.0
High Case									
Station numbers	L/MDV	60	73	100	200	596	975	1,357	1,746
	HDV	2	10	26	98	227	443	688	844
New station capacities (t/day)	L/MDV	1.5	1.5	1.5	1.7	2.4	3.0	3.0	3.0
	HDV	4.0	4.0	4.0	6.0	10.0	10.0	10.0	10.0

FCEVs and Hydrogen Refueling Per Station

Since the number of stations built at least through 2030 is tied to providing sufficient geographic coverage for driver convenience, in early years these stations will be capable of serving many more vehicles than actually are on the road, even in our High Case scenario. An important question becomes how many vehicles this number of stations can actually serve each day compared to their potential and compared to the needed number of customers to break even on cost and remain bankable. If the quantity of customers each day is too few, even if stations cover their operating costs, they will lose money, either on an operational cost basis or due to a low ROI.

In our technical analysis and projections, LDVs appear likely to require between 0.5 and 1 kg/day of hydrogen, with an average of around 0.75. This estimate is based on annual driving levels and in-use efficiency across a range of LDV classes. Under this assumption, a 1.5 ton/day station operating at 80% utilization rate, and thus dispensing 1.2 tons/day, should be able to serve 1600 vehicles per day. As the station sizes increase, more vehicles can be served. For HDVs, a 4 ton/day station operating at 80% utilization can provide 3.2 tons per day, and if vehicles refuel at an average of 40 kg, this size station will be able to serve 80 vehicles per day.

An 80% utilization rate here is meant as the percent utilization relative to whatever may be the maximum a station can achieve given the tendency for vehicles to refuel at certain hours, and not others. Whatever the actual maximum practical utilization rate of a given station, we assume 80% of this is an adequate level for the station to be profitable, and use this estimate in this analysis as a target. In realty, in a long-run equilibrium situation, and a mature market with hundreds or thousands of stations, average station utilization rate may be much lower, especially after there are more than enough stations to serve existing vehicles, and companies compete on price, location, etc. This appears to be the case today with gasoline and diesel refueling stations. For example, if long run profitability can be achieved at 50% utilization rate in a competitive industry, the equilibrium would likely eventually reach that level. Though such a detailed analysis of profitability and final equilibria are beyond the scope of this paper.

Finally, the growth in vehicle sales needs to align with (or be led by) this growth in refueling stations. There is a complex relationship between having enough vehicles to ensure station profitability and having enough stations to ensure vehicles can be adequately served and find stations as needed. An underpinning philosophy, at least over the next 5-10 years, must also be that stations roll out as quickly as possible to ensure that FCEV owners have adequate refueling choices, which will attract more people to buy the vehicles.

Station rollout compared to FCEV rollout, by scenario

As shown above, we project station rollout for LMDV and HDV stations to increase to 2030 to meet geographic needs, and thus it happens regardless of the numbers of vehicles that appear on the road, though in the High Case, this increase begins to be driven shortly before 2030 by the rising need for sufficient refueling capacity (apart from station numbers). It should be noted that, for vehicles to travel outside California, additional stations will of course be needed; these are not included in the present analysis and would presumably need to be justified by the use of those stations by vehicles within each state.

We created Figure 2 below to compare the number of LMDV stations constructed to meet geographic requirements (175) to the minimum number needed to provide fuel at an 80% utilization rate as quickly as possible, and thereby maximize economic returns. This analysis of the Base Case shows that the actual station buildout through 2030 is considerably above the minimum based on fuel demand, and the utilization rate of stations is very low for a number of years as a result. A target of 175 stations is hit by 2030, then the buildout pauses until the underlying demand grows to the point where more stations are needed for overall refueling capacity. This drives buildout expansion starting around 2032. This also drives some increase in average station size, which rises from about 1.5 tons/day in 2030 to 2.5 tons/day by 2050.

Figure 3 adds in the High Case (green line), with faster vehicle sales and stock growth, and thus a shorter period of time when there are “excess” stations. The green line in this case shows demand catching up to station numbers by about 2028. The area between the yellow and green line reflects much less excess capacity during that time frame and is considerably smaller than the gap between the yellow and red line of the Base Case.

In the Base Case, there is a total system overcapacity that rises to a peak of about 100 tons/day by 2030, then drops back to near 0 by 2032 as demand catches up. In the High Case, the excess only reaches about 50 tons/day by 2026 and is eliminated by 2028.

This excess capacity means unrecovered costs for station operators. Or it could be expensive from a policy point of view, if subsidies are used to eliminate or reduce station operating losses. These are risks that must continue to be weighed and addressed, as California seeks to develop a hydrogen refueling system that is ready in time to support FCEV development that enables reaching state ZEV targets.

Figure 2. Base Case stations built vs minimum needed to provide fuel, and utilization rate

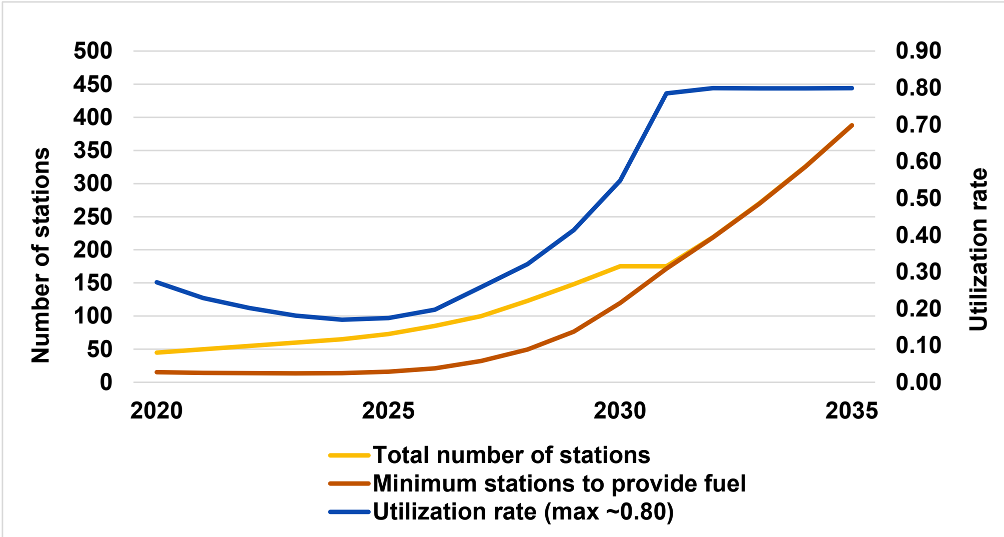
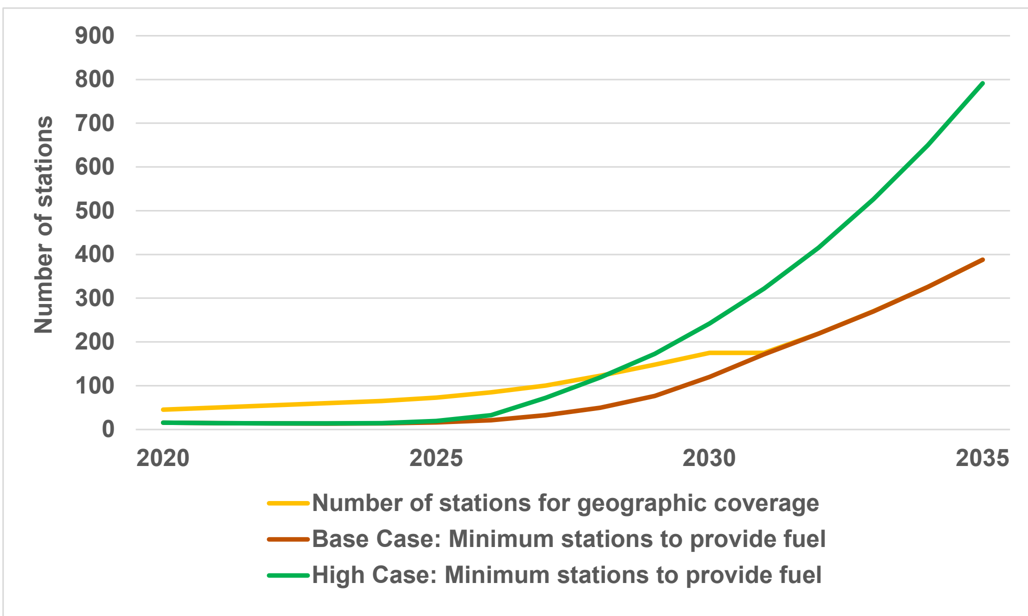


Figure 3. Base and High Case stations built vs minimum needed to provide fuel



Investment costs to achieve geographic coverage for LDV stations

Constructing stations early to meet geographic coverage requirements and ahead of actual fuel demand will require additional investment over the minimum development costs (if stations were added only when there was sufficient existing fuel demand to achieve immediate profitability). To estimate such costs, we have applied station construction and operating cost scenarios, and related these to annual fuel sales given projected demand. The station cost estimates and projections are based mainly from developing runs of the HDSAM Model developed by Argonne National Lab (ANL 2024), and as reported in this recent paper by NREL (2024). As shown in Table 4, we created a set of estimates and projections for station capital costs and operating costs by station size, type and year of construction to 2040 (costs constant after that year). As shown, the average size of LH2 (primarily HDV) stations, is more than twice the size of CH2 (used for LMDV) stations. Both grow in average size over time, as the market grows.

Table 4. Cost assumptions used in station analysis

	CH2 Stations			LH2 Stations		
	2023	2030	2040	2023	2030	2040
Average new station capacity (tons/day)	1.5	1.5	2.5	4	5	10
Capital cost (thousand $/kg/day of capacity)	$ 4.7	$ 3.6	$ 3.0	$ 2.7	$ 2.4	$ 1.8
Capital cost per kg produced at 80% utilization	$ 2.1	$ 1.6	$ 1.3	$ 1.2	$ 1.1	$ 0.8
Fixed OPEX at 80% utilization ($/kg)	$ 0.9	$ 0.8	$ 0.7	$ 0.8	$ 0.7	$ 0.6
Variable operating cost ($/kg)	$ 0.8	$ 0.7	$ 0.5	$ 0.6	$ 0.5	$ 0.4

When applying these station sizes and capital costs, Figure 4 shows the “excess” investment cost above that required for the minimum total station numbers, if no geographic coverage requirements existed. This excess investment occurs until targets for geographic coverage are achieved (roughly 175 for LMDV and 50 for HDV stations). This is shown in the figure in terms of additional annual investment and cumulative investment needed over time. The annual excess reaches about $80 million per year by 2027, then eventually goes negative since stations will now exist that would otherwise have been built later. The cumulative excess investment reaches $400 million by 2030/2031 that then drops and re-aligns to the base amount by about 2033. This analysis suggests that the need for early station investments is large, and there is risk of substantial economic losses associated with this period (about 2024-2034) while the utilization of the stations is low.

However, in the long term, the potential "excess station" problem may represent a relatively small cost compared to the overall size of the station market and total investments, expenses, and revenues related to the eventual mature system. But while stations lose money, it represents a large sum to the operators.

Figure 4. Additional LMDV Station Investment Over Minimum Needed, on an Annual and Cumulative Basis

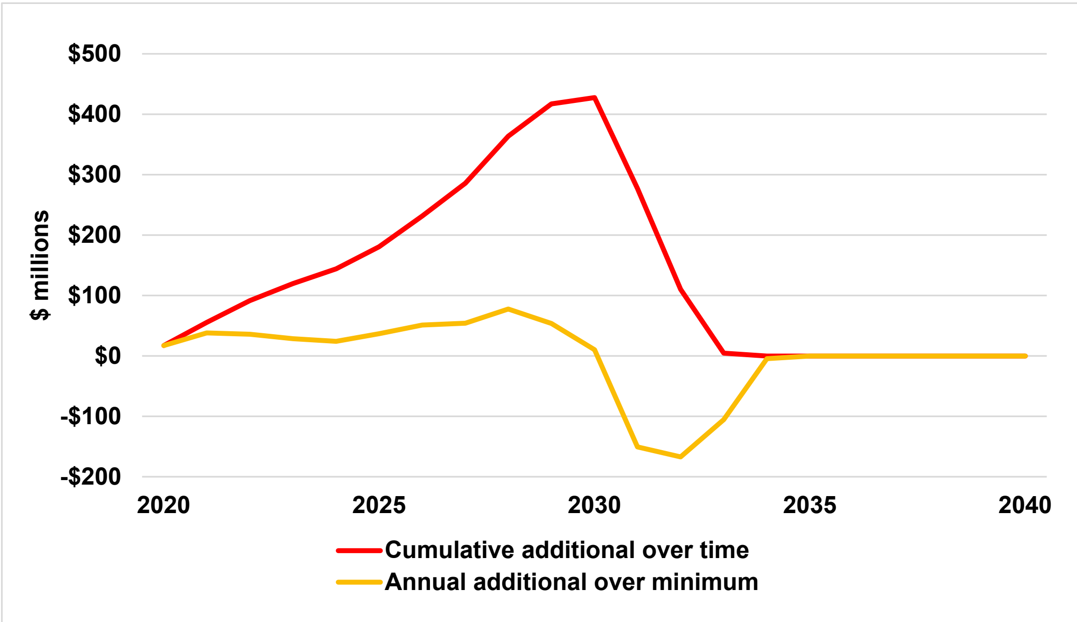
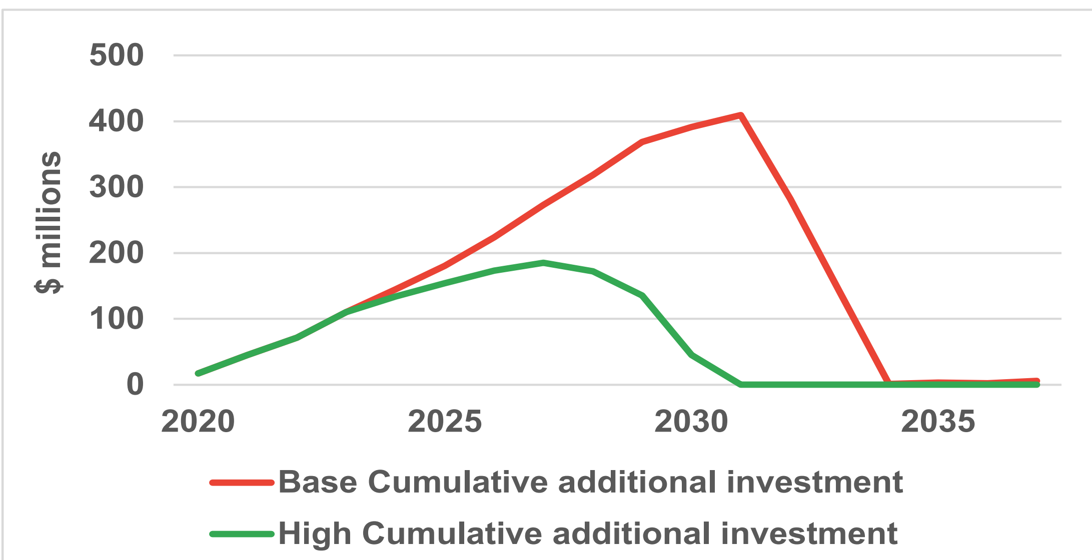


Figure 5. LMDV Station Investment on a Cumulative Basis, Base vs High Case

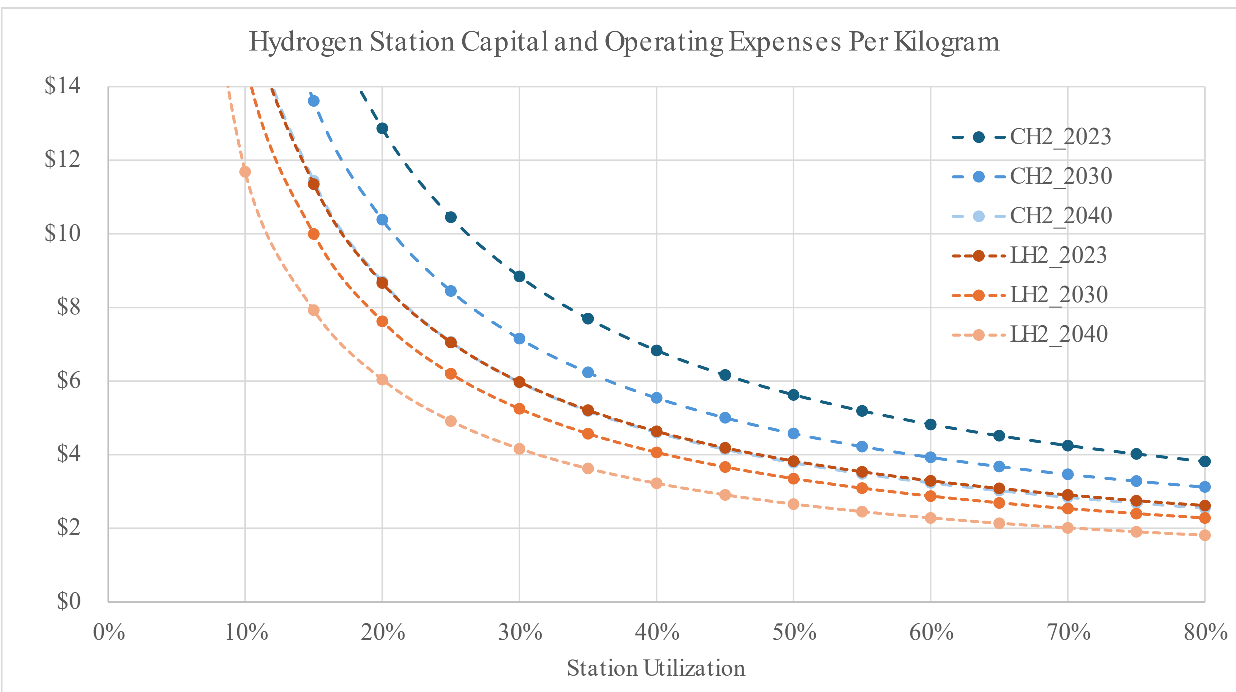


LDV Station Profit Calculations

Given the cost of building and operating stations, and a given hydrogen price (and specifically, a station price markup for each kg of hydrogen sold) then the profits of a station, or its rate of return, can be calculated. Here we use a simplified approach based on a base hydrogen cost markup of 30% over station costs, which would be expected to provide a "normal" rate of return at 80% utilization rate. If sales volumes drop below 80% utilization, profits will drop and eventually go negative below a certain sales level. However, if the markup per kg sold is increased beyond the base markup (that used at 80% utilization rate), normal profits could be achieved at lower sales volumes and utilization rates. But if the markup is fixed at the 80% CF level (such as because the market is competitive and the station is a price taker), then at that markup, lower sales will result in losses. These losses could lead to financial nonviability of the station operator, or could be covered by incentive funds or other government support for station operators.

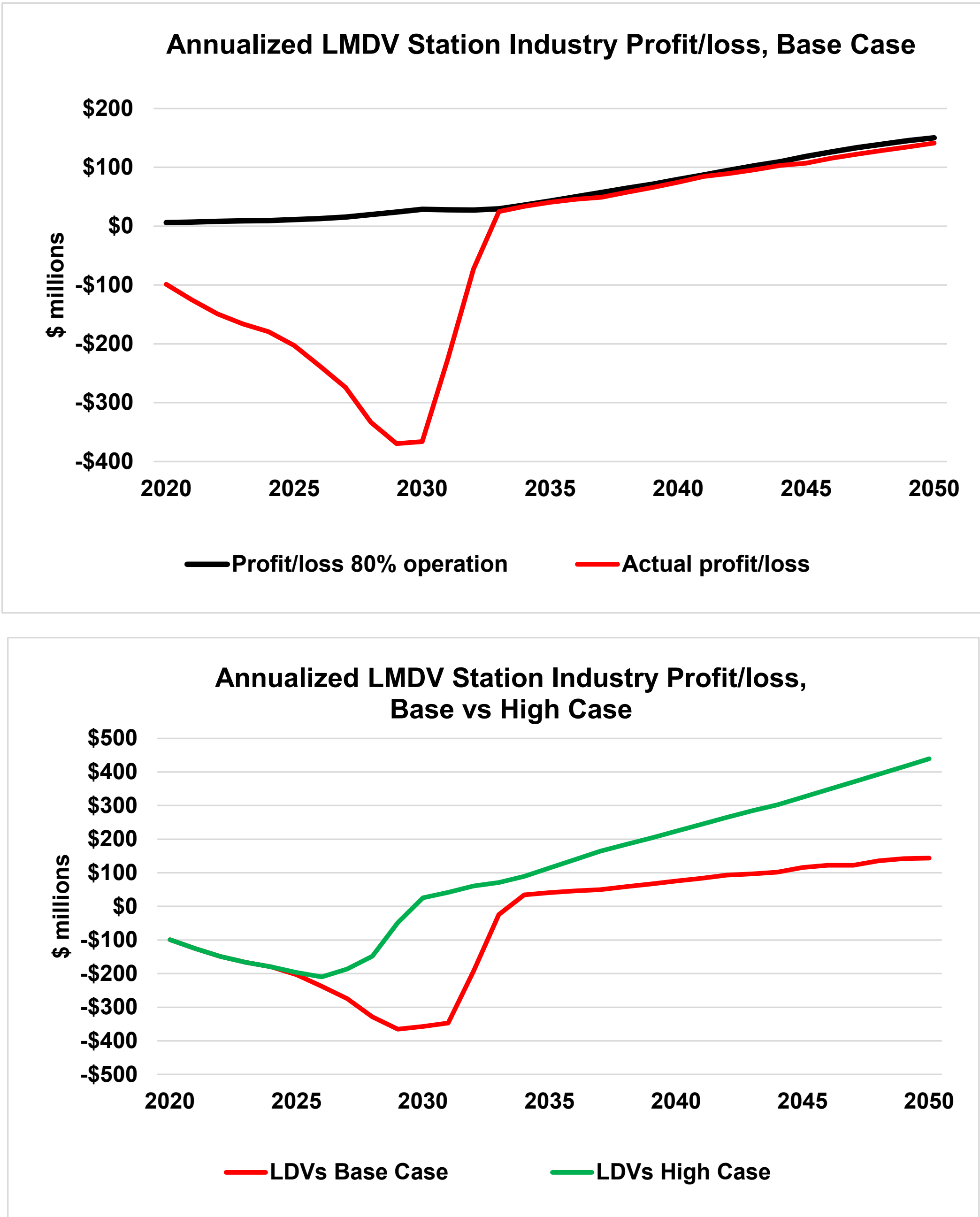
Our basic inputs for the profitability analysis are shown above in Table 3. Another way to show this is as a rising per-unit cost factor at lower station utilization levels. Figure 6 shows the specific net cost to stations given their capital and operating costs, and given the station utilization. The figure breaks these out by station type and year. This shows that costs rise rapidly if volumes processed are below about 50% of capacity. These are significantly higher as well in earlier years, and for CH2 (LMDV stations) than for LH2 (HDV) stations. But in all cases they can reach $14/kg or higher if the station utilization drops below 20%. The figure also shows that at high utilization rates (80%), the costs for CH2 (LMDV) stations are in the $3-$4 range per kg, and in the $2-3/kg range for HDV stations.

Figure 6. Hydrogen Station Costs as a function of utilization rate, technology, and year



Again, if the station sales drop below some level, the station would begin to lose money on every KG of hydrogen sold, unless it raises its markup (making the price of hydrogen to consumers higher, and likely slowing market growth). We consider both of these potential situations. First, if stations must absorb these additional costs at a fixed price of H2 sold (using the base markup but no additional markup), Figure 7 shows the annual and cumulative losses from low utilization rates by year in the base case, and (second figure) the annual losses in both the Base vs the High Case.

Figure 7. LMDV Station Industry Profit and Loss on Annualized Basis for Base Case and Base Case vs. High Case

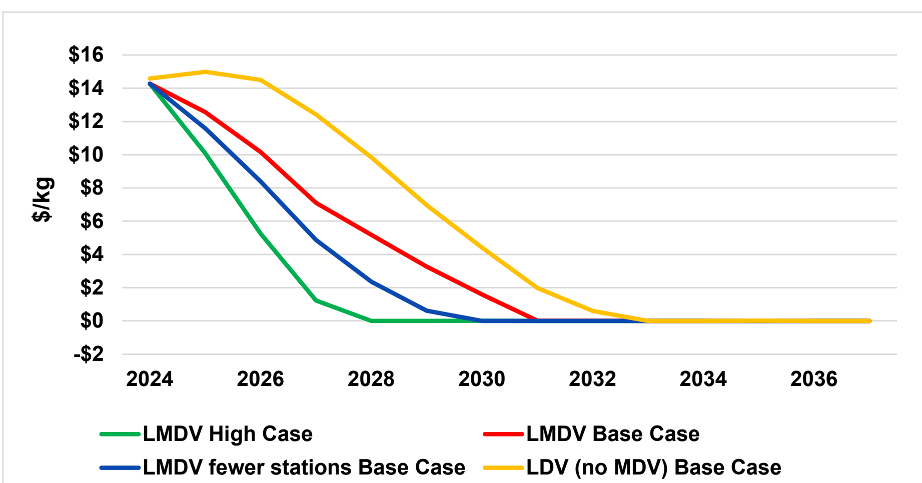


In the Base Case, the result is a strongly negative return relative to station costs in the first few years. This actually gets worse over time, due to the number of stations growing and the size of the investments increasing. Finally, by about 2034, the sales of hydrogen increase to the point where breakeven is reached. Profits then grow slowly with on-going expansion, and an on-going 80% utilization rate. In the High Case, investments are recovered much faster, with breakeven reached by 2030, and faster market growth leading to overall greater profits going forward than in the Base Case. The Base Case reaches a maximum annual loss of about $340 million in 2029-2031, while the High Case reaches a profit by about 2029, rising annually thereafter. The cumulative net losses (not shown) from 2023 until the breakeven year are about $2.8 billion in the Base Case and $1.1 billion in the High Case.

If station operators are in a position to increase their price markup for hydrogen sold to cover their full costs at lower utilization rates (as per Figure 6 above), the results are shown for LMDV stations in Figure 8. This begins at around $14/kg and declines over time as station utilization and hydrogen sales grow, but declines far faster in the high case than the base case. Two other cases are also shown: one with a much lower station buildout (to 100 by 2030 instead of 175), and one with the medium-duty vehicle hydrogen demand removed. The effect of cutting the number of stations to 100 is significant, but less so than increasing the number of vehicles and hydrogen demand (the High Case). And, with only LDVs using the stations, the decline in costs is significantly slower than in the Base Case, including those MDVs. This suggests that MDVs can play an important role, and stations should be equipped to serve them along with LDVs.

Overall these results suggest that once a station is built, having enough vehicles to support it each day is critical, so vehicle sales growth must follow soon after station construction, in general. Still, during early phases, pricing might have to become so high that it is not economically feasible to build the market (i.e., sales will not grow due to high prices and a subsequent lack of interest by consumers). In such a case, significant price supports would be needed to keep retail prices low enough to achieve the scenarios presented.

Figure 8. Hydrogen station "low-utilization" markup needed to make LMDV stations profitable, by year and scenario



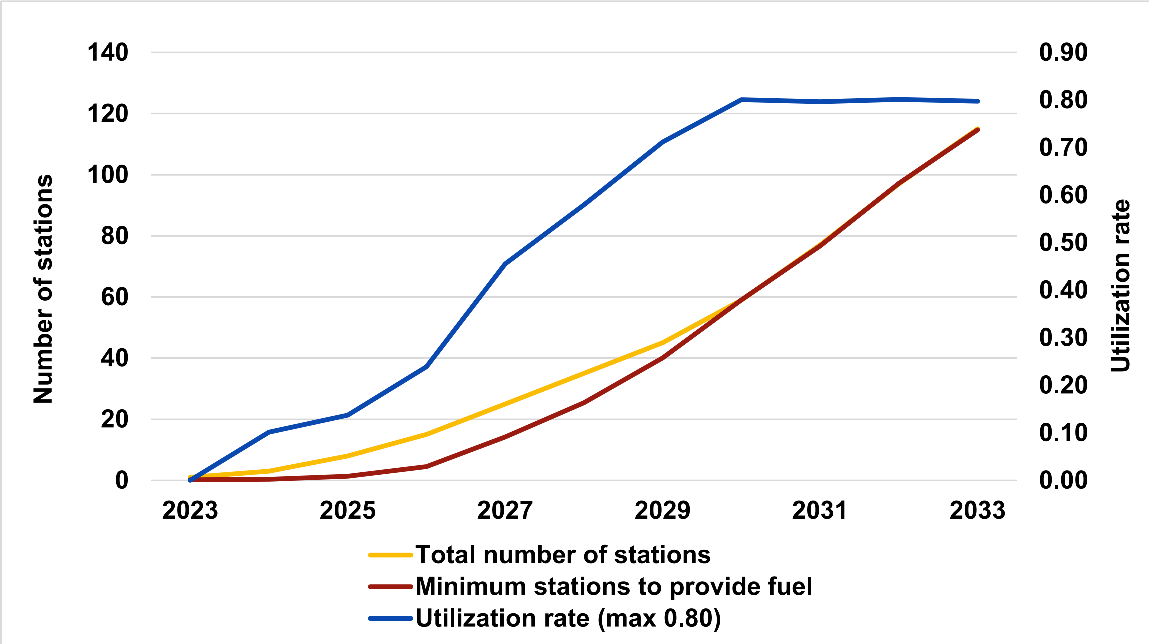
Heavy-duty Truck Station Results

As mentioned, an estimated 50 or more stations will be needed around the state by 2030 to refuel HDVs (including long-haul, day trucks, drayage trucks, and other class 7-8 trucks; this does not include buses) and to enable these vehicles to travel throughout the state. How refueling will be handled outside California when trucks cross the border into other states (and Mexico) will also need to be considered, although outside the scope of this report. These HDV refueling stations must compete on "dwell time" of trucks being refueled, currently at 12-15 minutes for typical diesel truck experience (in part because drivers use the refueling to attend to minor maintenance and other needs). To maintain such dwell times, HDV hydrogen stations probably will need to offer fast fueling technology since the large volumes (e.g., 30-40 kg) per refuel will require approximately 5 kg/minute or faster systems in order to achieve an overall 10-minute target. Using liquid storage at the station, and cryo-pump refueling technologies to achieve this (into typically 700 bar gaseous storage on vehicles) will affect station costs, though not change the needed quantity or locations of stations.

Applying the assumption of fully functional 4 tons/day HDV refueling stations, we examined HDV fuel requirements, the number of HDV stations needed, and the quantities delivered per refueling, and combined this data to yield varying conclusions regarding the total actual stations vs minimum needed, early utilization rates of stations, and resulting economics.

As shown in Figure 9, the gap between the minimum number of stations needed to provide sufficient fuel and the those needed for geographic coverage is fairly modest, reaching a peak point of 18 stations around 2027-2028 and closing altogether by 2030. The utilization rate also reaches 80% by 2030, and stations are added in line with growth in demand.

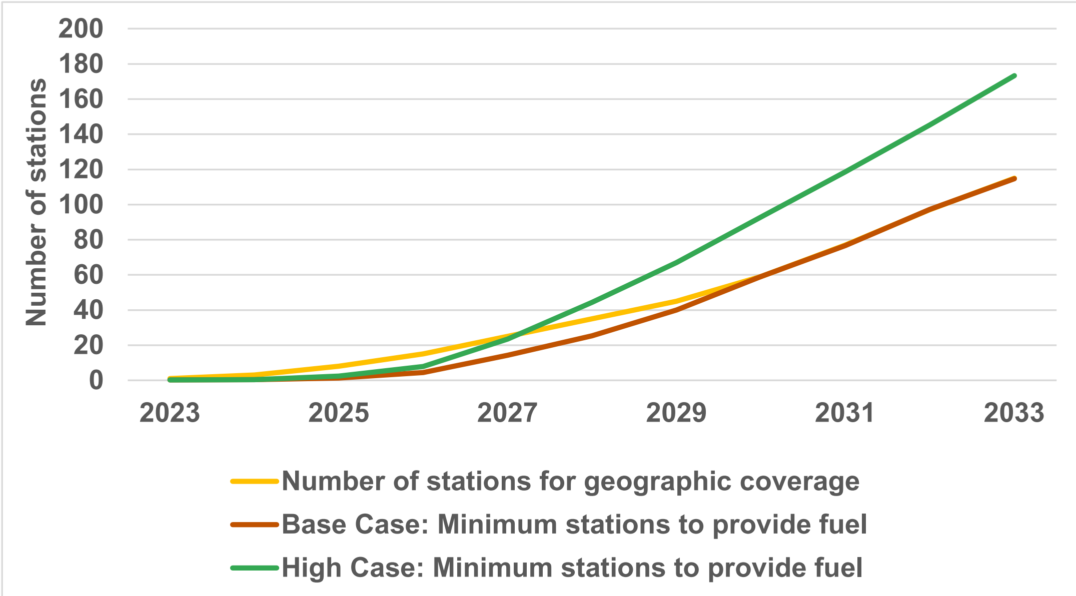
Figure 9. Number of HDV stations vs minimum required, with utilization rate



The gap is significantly smaller in the High Case, due to faster uptake of trucks, peaking at 10 excess stations in 2026, then declining until eliminated by about 2027. The area of excess capacity is shown in Figure 10 by the difference between the green lines from about 2023-2027, while for the Base Case it is between the yellow line and red line from about 2027-2030 and is about three times as large as for the High case as for the Base Case. The excess capacity of all stations peaks at about 40 tons/day in 2026, compared to 70 tons/day in 2028 in the Base Case.

Of course, these scenarios assume the indicated truck sales and stock growth rates described above. If truck sales and stock growth are slower than the Base Case here, but station buildout remains the same, it would take longer to reach the 80% CF target.

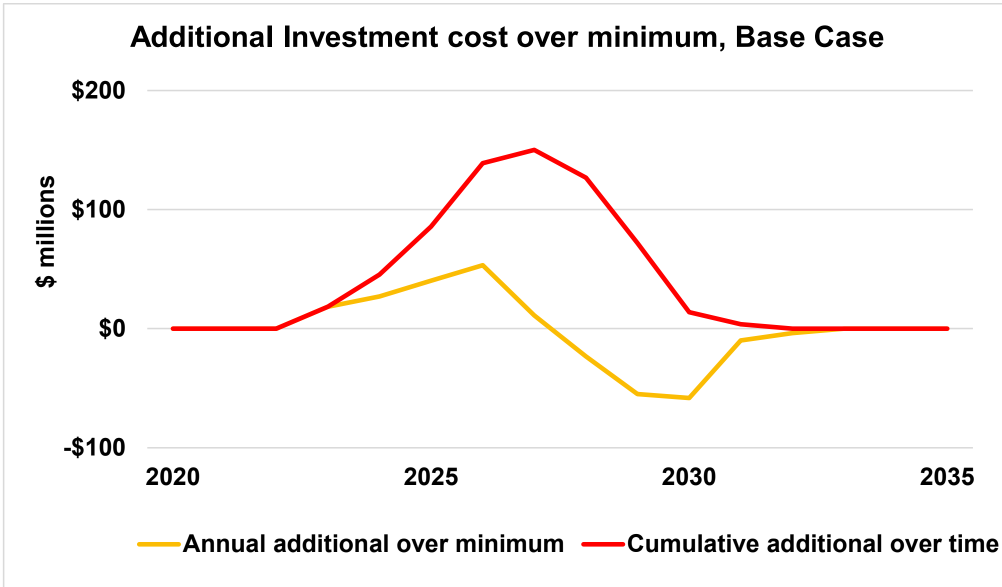
Figure 10. Base and High Case for HDV Stations vs. Minimum Stations Required

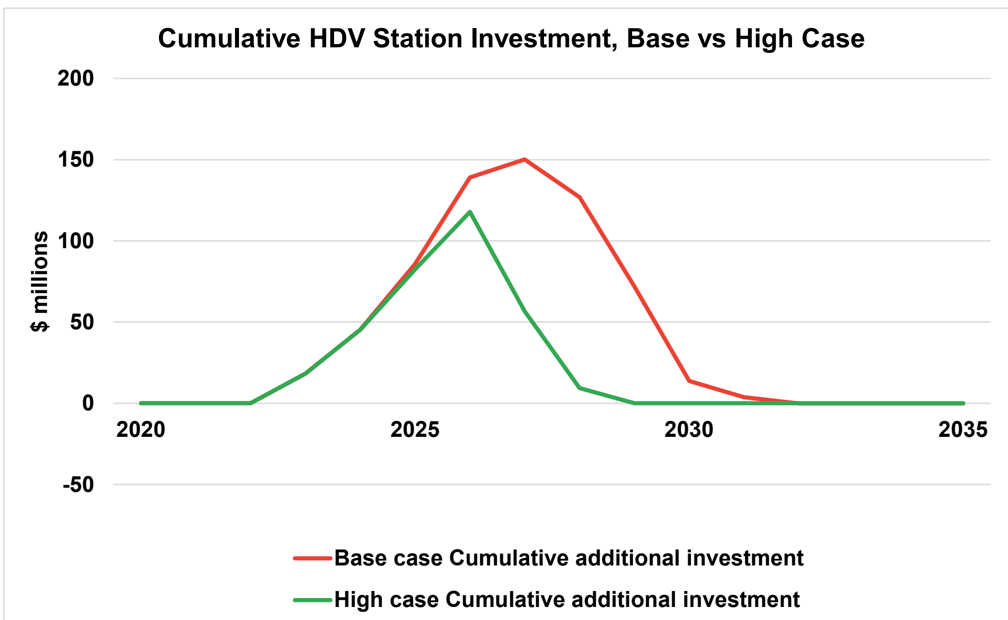


Notably, the LMDV Base Case shown in the section above does not achieve either station capacity of 80% or number of stations aligned with demand until much later, 2034, and the gap between total number of stations and those to provide fuel is far larger in the late 2020s than for HDVs. The LMDV Base Case shows overcapacity of about 83 stations and 160 tons/day of capacity in 2028, compared to overcapacity of only about 18 stations and 70 tons/day in that year for HDV stations. Moreover, this is for an overall higher assumed refueling level for HDVs (63 tons/day) than LMDV (52 tons/day) in 2028.

Using the per-station costs shown above in Table 3, the additional investment cost in the HDV Base Case is shown in Figure 11. The annual additional investment cost over minimum peaks in 2026 at about $40 million, and the cumulative additional investment over minimum reaches $150 million by 2028. This "excess" is eliminated by 2030, with the incremental costs in the late 2020s lower than what would have been needed without the extra early investment. As is the case for LMDV stations (shown above), the investment is pushed forward a few years to meet early geographic coverage needs. On a cumulative basis, it also remains higher, as those early station costs are higher than that of building later stations.

Figure 11. HDV Station Investment Costs Over Minimum for Base Case (upper figure) and Base Case vs High Case (lower figure)

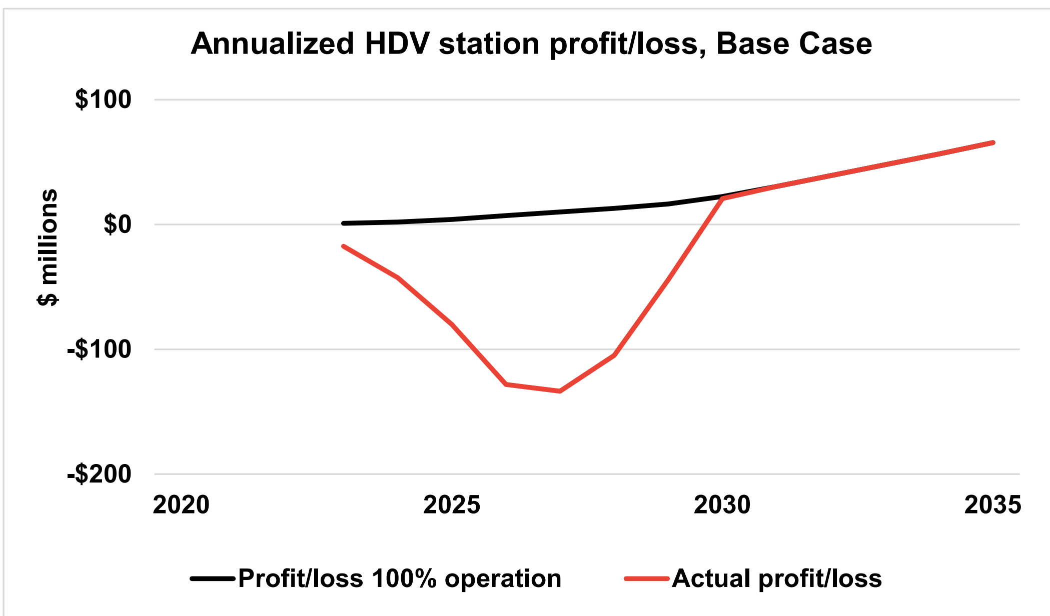


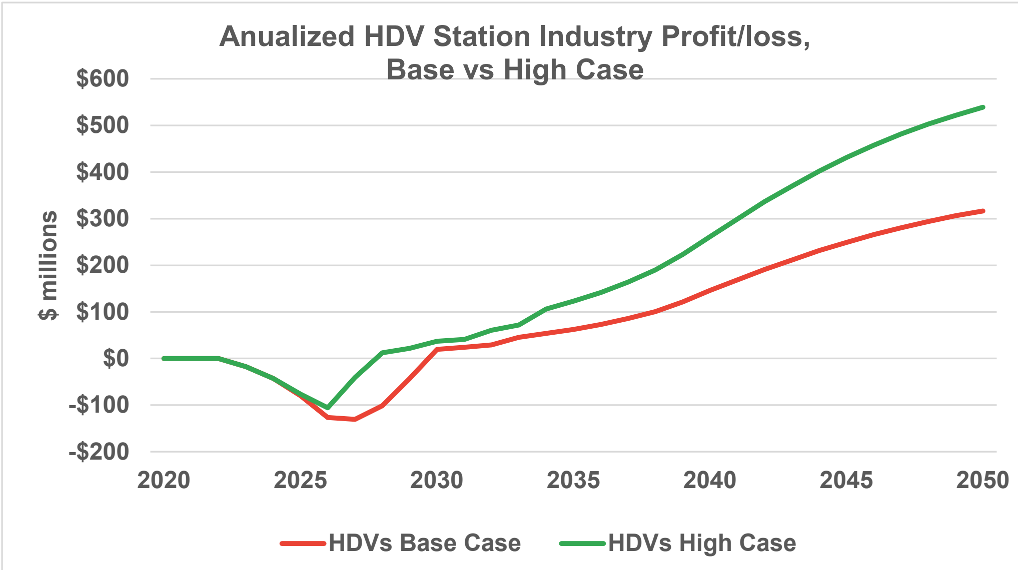


As done for the LMDV scenarios, we took into account the costs of HDV station investment and of operating stations on a daily basis, and estimated the profit or loss of station operation given the annual sales each year. The same assumptions as described above for LMDV stations were applied to HDV stations, except the current levelized cost for construction of HDV stations is estimated to be about \$1.3/kg instead of the \$2.1/kg for LMDV stations (Table 3). Fixed and variable operating costs are also slightly cheaper per kg for HDV than for LMDV stations.

For the HDVs, as for LMDVs, the Base Case result has a negative return in the first few years (Figure 12), which declines mainly due to investment growth. By about 2030, the sales market rises to the point where breakeven is reached. Profits then grow slowly with ongoing expansion, and an ongoing 80% utilization rate. In the High Case, investments are recovered faster, with breakeven reached by 2028, and faster market growth leading to overall greater profits than in the Base Case. The Base Case reaches a maximum annual loss of about \$130 million in 2027-28, while the High Case reaches about \$100 million in 2026. The cumulative net losses to the breakeven year are about \$650 million in the Base Case and \$300 million in the High Case.

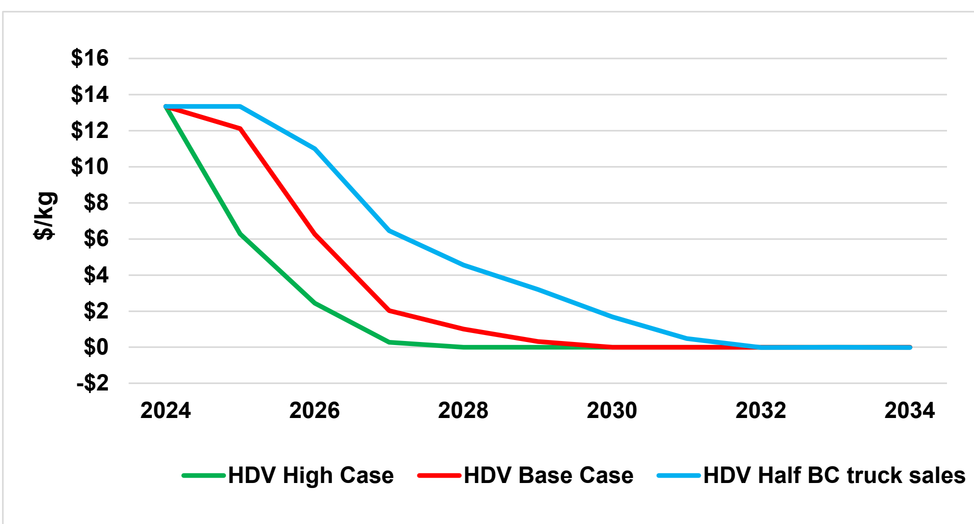
Figure 12. HDV Station Profit and Loss on Annualized Basis Base Case and Base vs High Case





Looking at heavy-duty station cost recovery from the point of view of additional markup per kg of hydrogen sold, Figure 13 shows the needed additional price added by year and scenario, starting around $13-14/kg in 2024. As discussed for LMDVs, this is a low-utilization markup, above the base amount needed to generate a profit at 80% capacity utilization, and is quite high when sales volumes are low. However, the additional markup for HDV stations drops more rapidly than for LMDV stations, for two reasons: 1) each truck added to the system generates 30-40 kg of additional daily hydrogen demand, compared to less than 1kg per vehicle (on average) for LMDVs; and 2) sales as a percentage of station capacity grows more rapidly for HDVs than for LMDVs relative to growth in station capacities. As a result, in the Base Case the low-utilization markup drops to zero by about 2030, and 2028 in the High Case, about 2-3 years faster than the case for LMDVs. We also include here a sensitivity case, showing how markups would evolve if only have the rate of sales occurred (resulting in about 2000 HDVs by 2030, rather than 4000). This slower cost reduction trajectory is closer to the LMDV base case, shown in Figure 8 above.

Figure 13. HDV Station Profit and Loss on Annualized Basis



Conclusions

In summary, this analysis has found that the need to expand station geographic coverage ahead of proportionate sales of FCEVs (both for LMDV and HDV stations) results in significant economic losses to station builders/operators until vehicle sales, use and refueling patterns can catch up. We find that it may be 2032 before enough light-duty hydrogen vehicles are on the road for the LMDV stations to become profitable, and 2028 for HDV stations, given the "Base Case" sales scenarios we consider. Faster sales growth in the High Case speeds this up by 2-3 years. We also find that HDV stations are inherently more cost efficient given their size, though most of their advantage in these scenarios is due to relatively faster uptake of HDVs, on a percentage basis, than LDVs or MDVs, and the fact that each vehicle uses 30-50 times more fuel per day than LDVs.

In the scenarios presented in this paper, the "catching up" of vehicle sales and hydrogen demand with station capacity is simply assumed to happen, but actual circumstances are more complex and will likely require a range of policies and marketing efforts to sell vehicles and grow this market quickly, even during periods of high vehicle and fuel costs. Many such policies are in place (such as ZEV purchase requirements, LCFS fuel and infrastructure credits, and others), but still more may be needed to ensure a rapid uptake of vehicles and to minimize the time window when stations are underutilized (along with maximizing other benefits of the vehicles). A follow-up analysis could focus on the relationship between the costs estimated here and existing policies to address these, and whether additional policies appear to be needed to close gaps.

This analysis is meant to be indicative, but directionally accurate. While most assumptions presented are fairly uncertain or picked as example scenarios, and reality will no doubt turn out differently, the direction of patterns like station utilization rates and costs are believed to be reasonable examples of what may happen. They suggest that station owner/operators will need to have some kind of financial assistance to get through a classic "valley of death" period, *i.e.* when investments have been made but profits take longer to achieve.

Our findings of economic advantages for HDV stations suggests that developing these, along with spurring hydrogen HDV sales, may hold promise for minimizing the period of station economic losses and helping to get the hydrogen refueling system into a profit regime. This could in turn help LMDV stations by lowering the cost of some components (via supply chain scale economies) as well as building out the hydrogen supply and distribution system, and hopefully lowering the price of hydrogen to stations, helping to spur the LMDV market along with the HDV market. Our scenarios suggest that around a $14/kg additional price would be needed in the near term when station utilization rates are quite low, but this drops quickly for HDV stations once HDVs are entering the market in significant numbers. It takes several years longer to eliminate this extra markup for LMDV stations, given our Base Case light- and medium-duty hydrogen vehicle sales scenarios.

The analysis here should be reviewed and updated as better information is available, especially as HDV stations start to be constructed in California over the next 2-3 years.

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