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A hydrogen hub for California: What role for fuel cell transportation?

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Executive Summary

By June 2023, California will have applied for a US DOE-funded hydrogen hub, the results of which may be known. The discussion of a hydrogen hub here (as of March 2023) does not reflect the proposal, and is more hypothetical, based on the results of UC Davis' analysis. We find that transportation hydrogen demand on the order of 500 tons per day may be sufficient for California to achieve scale economies adequate to achieve a cost-effective, self-sustaining hydrogen system. This in turn can be achieved with 5000-10,000 trucks and buses and 50,000 to 100,000 light duty vehicles. These targets can be achieved with substantial but feasible investments in hydrogen supply, distribution, storage and refueling infrastructure, along with the purchase and operation of the necessary vehicles. Other sources of demand such as rail, ports, and stationary sources can help build markets further but are not critical to develop the transportation hydrogen system or lower vehicle or hydrogen fuel costs to a sustainable and competitive level.

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1 Introduction

California, via its Alliance for Renewable Clean Hydrogen Energy Systems ($ARCH_2ES$) [1] and related initiatives, aims to develop a hydrogen system in the state reaching over 10,000 tons per day by 2050, and between 500 and 1000 tons per day by 2030. The transportation sector will play an important role in this system. This paper considers a potential scenario for transportation that, it is argued, can be achieved and will be sufficiently scaled to help reduce costs to achieve economic sustainability of the system. As of March 2023 this is a work in progress but concepts and key data are reported. More details will be provided in the presentation to be made at EVS in June 2023.

The transportation sector is the largest emitter of greenhouse gas emissions (GHG) in California, making up about 40% of total GHG, mostly from tailpipe emissions from cars and trucks [2]. When the production and refining of oil is considered, transportation's contribution to GHG rises above 50%. Transportation is also responsible for 80-90 percent of the state's smog-forming criteria pollutants that harm public health, especially in disadvantaged communities near freight corridors and ports. Therefore, no sector is more important for emissions reductions for both air quality and climate purposes.

While there are nearly 30 million light-duty vehicles in California, there are fewer than one million trucks, and around 250,000 heavy duty (class 7-8) trucks. Over 15,000 light-duty hydrogen fuel cell vehicles have been leased or sold [3], by far the most in any state in the US. Around five models of fuel cell vehicle (FCEV) are on the market, though to date, sales of FCEVs have been dominated by one or two of these. models. The number of LDV FCEVs has not grown much in the past few years, due to a lack of model variety, limited refueling station numbers (and low availability, often with only 2/3 of stations operating on a given day) costs of vehicles and fuels, and low general awareness. The state has been working to resolve the station issue, with over 100 stations funded and/or in development and a goal of 200 stations in service by 2026 [3]. Around 10-15 tons of hydrogen are dispensed daily to these FCEVs.

Though there are very few fuel cell trucks in service, a number of models are being launched (or expected to launch in 2023. The California Heavy Vehicle Incentive Program (HVIP) [4] has a list of FCETs that have qualified for funding that as of mid-March 2023 lists 5 fuel cell models, mainly in the heavy-duty truck class. Other models in other market classes are in development. There are almost 100 fuel cell electric transit buses (FCEBs) operating in the state, though this represents a very small portion of the total bus fleet of over 10,000. Presently, five agencies in northern and southern California operate 98 FCEBs, consuming approximately two tons of hydrogen daily.

Notably, hydrogen fuel for transportation is largely renewable, and hydrogen refueling has transitioned to renewable resources more quickly than battery electric charging. In 2020, an estimated 90 percent renewable content was achieved in hydrogen used for refueling in California though this dropped to under 70% in 2022, several operators were also operating that year at or near 100 percent renewable content. [5].

2 A Scenario for hydrogen and fuel cell vehicle use in California to 2030 and 2050

A long-term vision of hydrogen and fuel cell vehicle use in the transportation sector in California could range widely, but a reasonable view, consistent with CARB's 2022 Scoping Plan and regulations like Advanced Clean Cars 2 (ACC2) [6] and Advanced Clean Trucks (ACT) [7] is that FCEVs could account for 10-25% of the stock of LDVs by 2045 (when the vast majority of vehicles are mandated to be zero emission), and 50% or more of the stock of trucks and buses. The remainder would mostly be battery electric though some legacy ICE vehicles would also still be in use. Thus the vision is that FCEVs play a small but significant role for LDVs and a much larger role for trucks, especially heavy duty long haul trucks and buses. In the nearer term, achieving 10% of LDV ZEV sales and 20% of HDV ZEV sales by 2030, with up to 50% sales of ZEV buses (that must by 100% ZEV sales by 2029), appear to be reasonable targets.

Focusing on the 2030 numbers, how will such sales be achieved, and what does this mean for the stock of FCEVs in that year, as well as hydrogen demand and needed infrastructure to transport, store and dispense that hydrogen to the vehicles? What does it mean for the numbers of stations?

UC Davis has undertaken extensive modelling of this type of system in the 2030 time frame, and extending this to 2050 with the longer term targets [8]. We have looked at multiple sectors and a hydrogen system that covers them (transportation/electric power/industry/buildings). Here we focus on our "Base Scenario" for transportation. Other scenarios are available and will be published separately.

2.1 Fuel cell vehicle and hydrogen use

Below we present our results for sales/stocks/hydrogen demand for light/medium/heavy duty road vehicles. The logic behind the projections is shown in Figure 1 This figure shows a range of vehicle types and four variables for these:

a) The ZEV vehicle share of all LDV sales (that rises to 100% by 2035 and beyond),

b) The 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)

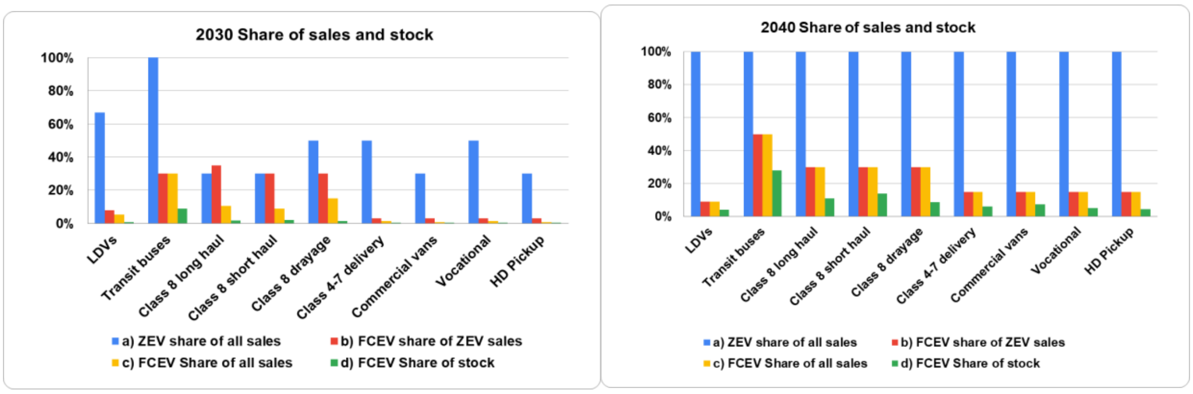


Figure 1. ZEV shares of sales, FCEV shares of ZEVs, for 2030 (left) and 2040 (right) in Base Scenario

The ZEV market shares reflect current policy and law in California. In 2030 the overall ZEV share of total LDV sales must reach nearly 67%; it must reach 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 much less clear and FCEVs wil compete mainly with battery electric vehicles (BEVs) to gain market share among ZEV sales. This FCEV market share is generally projected to be quite low, at about 5% for LDVs and other smaller trucks, and at 25% or 30% for larger trucks and buses at least through the 2030 time frame. These shares drive the total sales assumptions in this scenario and were set to provide a plausible yet significant trajectory for projecting FCEV sales. By 2045 they reach somewhat higher sales shares, typically double (or more) of the 2030 levels, and the stocks grow to catch up, reaching 20% or more for major truck types (and about 7% for LDVs, following 10% sales shares in that year).

The high FCEV case, shown in the body of this report, has about 2–3 × the ZEV sales shares for FCEVs by 2040 as shown in this scenario. This "base" scenario is particularly interesting since it turns out to be sufficient to provide reasonably high hydrogen demand by 2030; demand that, as will be shown next, may be sufficient to achieve levels of production that can lead to a commercial market.

By 2040, manufacturers of all vehicle types will be required to sell only ZEVs; we assume FCEVs will reach 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 then remains fairly constant to 2050 (though stock shares still rise).

For trucks, which are a major focus of ARCHES, we expect most of the sales of FCEVs over the next 7 years to be mainly in the heavy-duty tractor-trailer or "straight truck" classes (rather than vocational or smaller delivery classes). Overall, we estimate that about 100,000 class 7-8 trucks (of all technologies) will be sold over this 7-year period; with a target of 5% of ZEV sales, this would total about 5000 FCETs. The number of fleets that would purchase these trucks, the typical number of trucks per fleet, and the number of trucks produced by individual OEMs, in order to achieve economies of scale, are open questions. But strong support from fleets (in purchasing) and OEMs (in supplying) the trucks is clearly critical. The numbers needed to bring costs and prices to a competitive level will be tracked and refined over time when more fleet operators start to deploy fuel cell trucks

The stock growth of various truck types and transit buses associated with this scenario are shown in Figure . Heavy duty FCETs and buses reach about 10,000 stock by 2030 and over 100,000 by 2050; smaller delivery and commercial pickup trucks (with much larger markets generally) reach 30,000 in 2030 and over 600,000 by 2050. LDVs (not shown, since they would dominate and compress the other modes in the figure) reach 275,000 stock in 2030, 800,000 in 2035, and 1.7 million in 2050, about 5% of the stock of LDVs in California at that time. Sales of all these vehicles types are commensurate with building these stocks, and reach on the order of 10,000 trucks per year and several hundred thousand LDVs per year by 2030. Reaching these sales levels will depend on the refueling infrastructure available along with the range of attributes that must be competitive, mentioned above, such as vehicle price, fuel price, and the number (and total supply) of each vehicle type, offered by manufacturers.

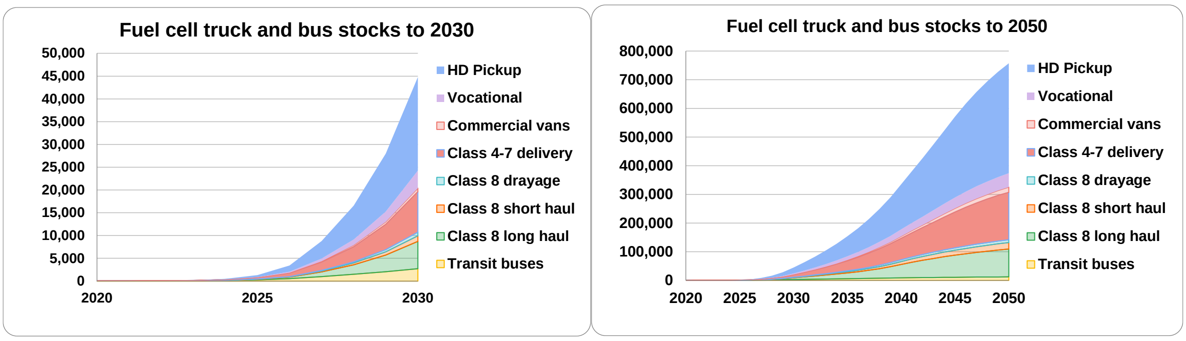


Figure 2. Fuel cell truck and bus stocks to 2030 and 2050, Base Scenario

Many transit agencies are operating or plan to operate fuel cell buses in California. From various discussions, 12 agencies appear ready to commit to more purchases, with a potential for 1000 fuel-cell electric buses (FCEBs) in operation by 2030 appearing realistic as part of an ARCHES effort. Looking ahead, there are many reasons to expect further cost reductions and greater competitiveness in the ZEV bus sector. FCEBs use a battery that is less than 1/6 the size of a battery-electric bus (BEB), while providing longer range, faster refueling, and consistent performance from full tank to empty, cold weather to hot. Fuel cells additionally maintain the battery state of charge, degradation and improving lifetime costs. According to a Foothill Transit analysis, fuel cell buses with hydrogen refueling infrastructure operated over a 12-year period instead of battery electric buses to cover a 23-bus block would result in a savings of $12.9 million.

As shown in Figure, the growth in the stocks of the various types of FC vehicles, given typical daily travel and efficiency estimates, results in hydrogen demands as shown, reaching close to 500 tons/day in 2030 and over 5000 tons/day in 2050. Most of this demand comes from LDVs and heavy-duty (especially long haul) trucks.

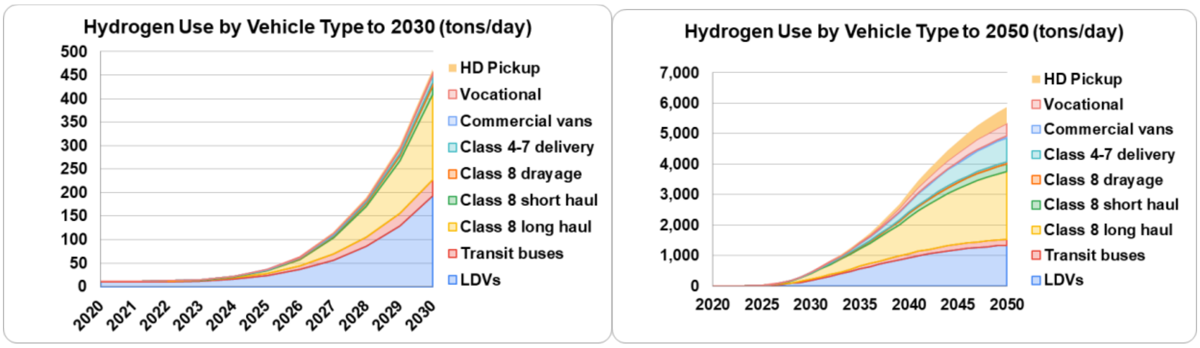


Figure 3. Hydrogen demand to 2030 (left) and 2050 (right) by vehicle type, tonnes/day

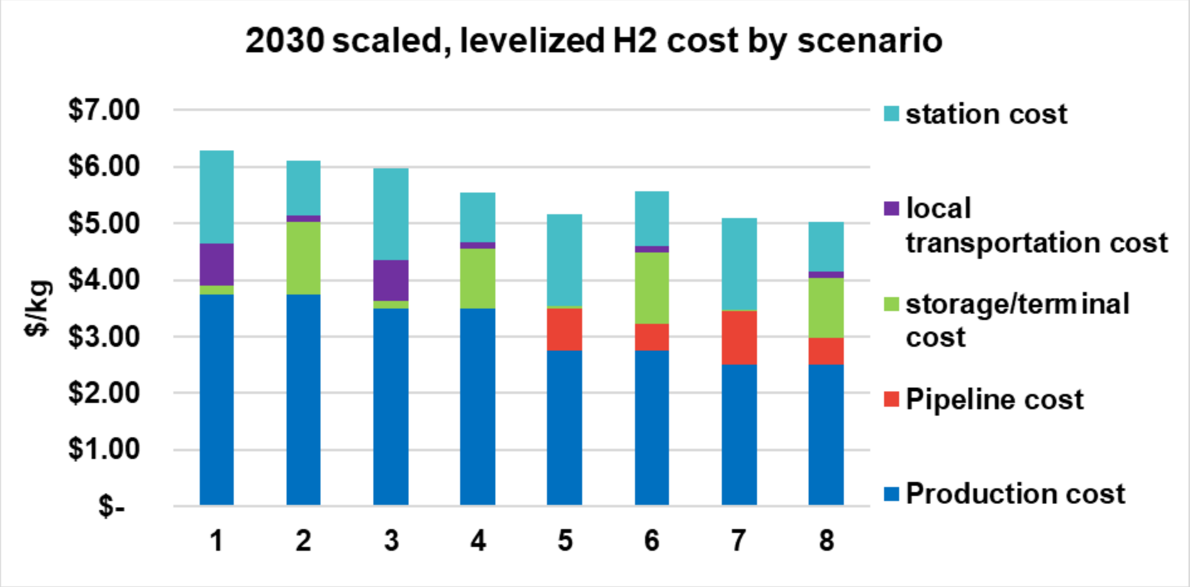
2.2 Hydrogen system design and cost

Given the hydrogen demand of close to 500 tons/day by 2030, is this enough hydrogen demand and system size to reach an economically sustainable and even prosperous hydrogen industry? We think the answer is "probably". A detailed cost analysis depends on assumptions about scale and learning. Ours suggests that this scale should be sufficient to bring costs and prices of fuel down dramatically from the $15/kg (or even higher) it has been in California during 2022/23 [9]. As a simple example, ten hydrogen production facilities sized at 50 tons per day by 2030 would be enough to supply the hydrogen for these vehicles, which is a reasonably large volume both in terms of the both the size and number of facilities. However, the scaling and learning effects, and thus the cost and price of the hydrogen, will ultimately depend on the production technologies and their costs, such as the cost per kW for electrolyzers, and the price of electricity, both of which depend on things that are outside the scope of this scenario. And yet, if California can develop a hydrogen market big enough to support 10 fairly large production facilities and the distribution systems to get this hydrogen to end uses, the cost of this system should drop fairly dramatically compared to the current situation.

As shown in Figure 4, a range of possible system configurations is considered for delivering hydrogen from production locations to end uses, varying: (i) whether hydrogen is produced nearby end uses (and shipped by truck), produced far away and shipped by pipeline to either terminals or directly to end uses; and (ii) whether the system relies mainly on a gaseous distribution system or liquefies hydrogen at terminals and handles it as a liquid at stations, and for refueling of vehicles (even if it is stored as a gas on vehicles).

The estimated costs of the systems, based on their components and other configuration aspects, in 2030, are shown in *Figure 1*. The costs associated with each segment of producing, storing, or moving the hydrogen were estimated using a range of models and off-line analysis described in our forthcoming larger report.

The figure shows eight scenarios as described in the table below the figure. These different approaches to producing electrolytic hydrogen and delivering it to refueling stations (and onto vehicles) range in net, levelized cost delivered from about \$5.00 to \$6.25 per kilogram. This reflects a scaled system in 2030 and depends on a range of assumptions, such as the ability (in four of the scenarios) to construct long-distance pipelines in that time frame.



	1	2	3	4	5	6	7	8
system tons per day	500	500	1000	1000	500	500	1000	1000
liquid or gaseous dominated	G	L	G	L	G	L	G	L
Nearby or distant production	N	N	N	N	DP	DPT	DP	DPT
Number of stations	300	200	600	300	300	200	600	300
Average station size (kg/day)	1.67	2.50	1.67	3.33	1.67	2.50	1.67	3.33
Average distance	50	50	50	50	1000	500	1500	500
Electricity price	\$ 0.06	\$ 0.06	\$ 0.06	\$ 0.06	\$0.03	\$0.03	\$0.03	\$0.03
Electrolyzer cap factor	67%	67%	67%	67%	33%	33%	33%	33%

Figure 1. 2030 levelized H2 cost (\$/kg) by production/distribution scenario.

(Notes: G=H2 transported as a gas; L= transported as a liquid; N=hydrogen produced nearby, DP=hydrogen produced at a distance and moved by pipeline; DPT= hydrogen produced at a distance, moved by pipeline and stored at a terminal.)

Achieving a \$6.00/kg or lower price at refueling stations, and taking into account the efficiency advantage that fuel cell vehicles have over gasoline and diesel vehicles, should make FCEVs competitive on fuel cost with those liquid fuels; however, it will be difficult to compete with electric vehicles given their efficiency advantage and low cost of energy, except in cases where electricity prices are very high, such as (potentially) some fast recharging locations. But overall, the scenario suggests that fuel cell vehicles should be capable of achieving market competitiveness on fuel price.

2.3 Fuel cell vehicle costs

Regarding the purchase cost of light- and medium-/heavy-duty FCEVs, we estimated the incremental purchase costs along with operating (maintenance and fuel) costs, to derive an overall "incremental" cost of hydrogen vehicles vs gasoline or diesel vehicles in these scenarios (Figure 5). Here we report the incremental purchase costs, which are fairly high per vehicle in the early years (e.g., 2025) but drop to near-equal or even lower than gasoline or diesel as FCEV purchase prices reach parity or better. Using basic assumptions about scale and cumulative production of vehicles and the fuel cell systems in these vehicles, we estimate that production runs on the order of several thousand for trucks and a few tens of thousands for LDVs in 2030 should be sufficient to drive down vehicle production costs (and thus prices) considerably. T

Our projected relative prices are shown for light-duty (upper left) and a range of truck types (upper right). The light-duty also illustrates the relative price of FCEVs to both gasoline and battery-electric vehicles, indicating they all reach a similar level by the early 2030s. Though these incremental purchase prices start higher, their reduction over time as sales increase results in less overall incremental cost than one might expect. The overall cost of purchasing all the FCEV cars and trucks is shown in the lower two panels of Figure 5. Total cost reaches $4 billion per year in 2030 and a steady $8 billion per year for new FCEV purchases by about 2040, when the system matures. But the incremental cost of these vehicles over their gasoline/diesel counterparts is $200 million, reached in 2035, and by 2040 they reach overall parity across vehicle types (net $0 additional purchase cost). Thus the net "investment" cost of these vehicles is far lower than their gross purchase prices would suggest.

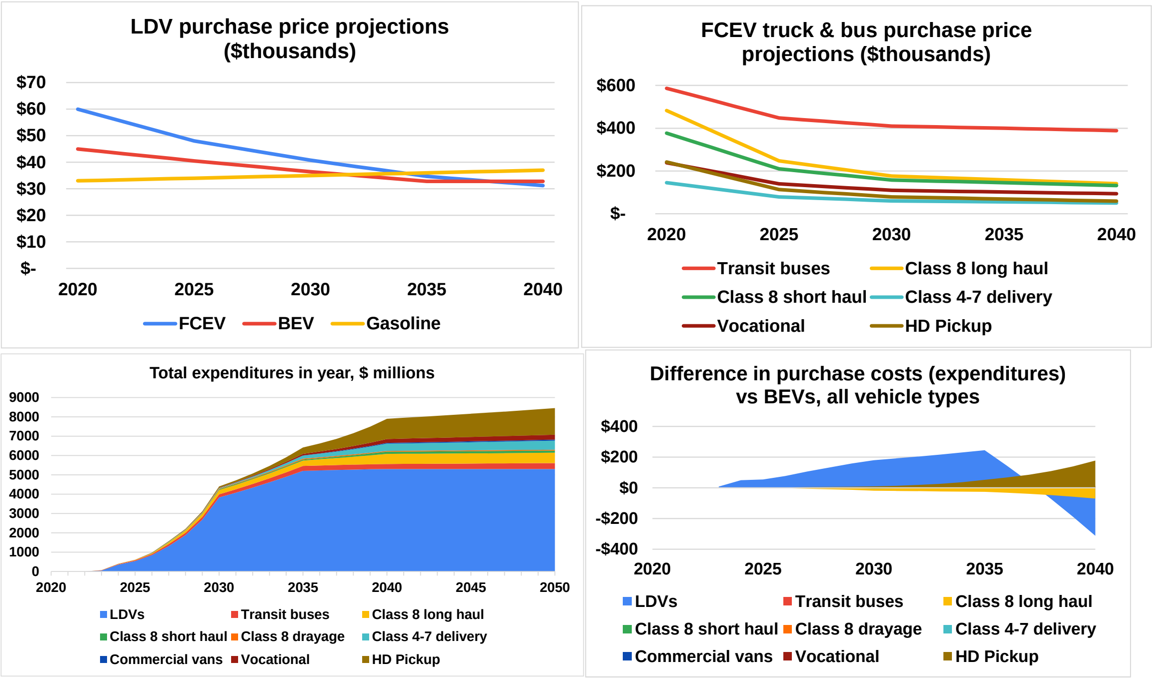


Figure 5 Vehicle prices and purchase costs in the scenario (HD, heavy-duty)

3 Summary and Conclusions

Drawing on our modelling study of a hydrogen system for California, we have presented one example scenario, though with many possible variants in terms of the fuel supply chain. This "Base Scenario" provides a sense of the scale and costs of for a hydrogen system that could be built by 2030 and serve the transportation sector in California. Larger systems are possible, and our high case in the main report considers such a scenario. There could also be a similar level of demand from investments in hydrogen for industry, and particularly for electricity generation, in the 2030 time frame.

We find that the transportation scenario presented here could lead to sufficiently large numbers of fuel cell vehicles by 2030 to reach a competitive level with up-front costs comparable to competing vehicle types; and to an infrastructure scale to bring down the costs of hydrogen to a level that should also help make FCEVs a viable option for households and fleets. However, policies may still be needed to close existing price gaps with the costs and prices of other vehicles, particularly electric vehicles. On the other hand fuel cell vehicles will have some non-cost advantages over electric vehicles, such as driving range and refueling time, which may help justify some higher costs of purchase and operation.

After 2030, a much bigger scale-up is envisioned in the scenario, and by 2050 there are around 10 times more vehicles and 10 times more hydrogen used than in 2030; this very large system should have a good chance of achieving optimal long run, low cost system operation. Fuel cell vehicles may eventually become cheaper to purchase than electric vehicles, though operations and fuel costs per mile appear unlikely to ever drop below those of EVs for most types of vehicles.

Additional work is needed to better understand how scale and learning will affect costs, the policies and policy-related costs of achieving self-sufficiency, and how and when the hydrogen system for transportation can become self-sustaining. Time and experience will also provide insights, as vehicles and fuel infrastructure roll out over the coming 3-5 years. The US DOE Hubs initiatives are thus very important from this point of view. Prices should improve over this period, if a significant number of trucks and buses, and fueling for these vehicles, is implemented. Growth in LDV fuel cells/hydrogen will also be important to help scale up the whole system.

4 References

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Presenter Biography

Lewis Fulton has worked internationally in the field of transportation, energy, and environment analysis and policy development for over 25 years. He is Director of the Sustainable Transportation Energy Pathways Program (STEPS+) within the Institute of Transportation Studies at the University of California, Davis. There he leads a range of research activities around new vehicle technologies and new fuels, and how these can gain rapid acceptance in the market. He also coordinates research across five STEPS+ Centers: Energy Futures Center, the Sustainable Freight Center, the Plug-in Hybrid & Electric Vehicle Research Center, the 3 Revolutions Future Mobility Program, and the China Center for Energy and Transportation. He has previously worked for the International Energy Agency, UN Environment Program, and US Dept. of Energy.