To: San Francisco Technical Working Group (SF Environment, SFMTA)
From: Logan Pierce, Peter Slowik, Stephanie Searle, International Council on Clean Transportation
Date: January 31, 2023
Re: Electric vehicle market direction (final memo)

INTRODUCTION

The global transition to zero emission vehicles (ZEVs) continues to accelerate. In 2021 global light-duty ZEV sales, which include battery electric, plug-in hybrid electric, and fuel cell electric vehicles (i.e. BEVs, PHEVs, and FCEVs), totaled over 6.7 million, almost doubling the global ZEV market share of 4.2% in 2020 to 8.3% in 2021.[1] Similarly, in the United States (US) the light-duty ZEV market share increased from 2% in 2020 to 4.4% in 2021.[2] In the US, light-duty vehicles (LDVs) account for nearly 90% of all vehicle miles traveled (VMT) and more than half of greenhouse gas (GHG) emissions in the transportation sector, the highest polluting sector.[3] A widespread transition to all ZEVs is thus needed to address pressing air quality climate change obligations.

The Biden administration has passed both the Bipartisan Infrastructure Law and the Inflation Reduction Act, investing $7.5 billion to build out a network of 500,000 electric vehicle (EV) chargers across the country and creating a $7,500 tax credit for newly purchased ZEVs to support its goal for US ZEV sales to reach 50% of all new LDV sales by 2030, among other provisions, to encourage the transition to EVs.[4] California alone represents about one third of all new US EV sales, and the state's ZEV market share was more than 12% in 2021. In August 2022 the state adopted its Advanced Clean Cars II (ACCII) regulation to have 100% ZEV sales by 2035, becoming the first state to do so.[5] San Francisco is on the leading edge of this

1 "Global EV sales for 2021", EV-volumes.com, accessed December 21, 2022, https://www.ev-volumes.com/news/ev-sales-for-2021/.

2 Alliance for Automotive Innovation, "Get Connected: Electric Vehicle Quarterly Report (Q4)," (March 2022), https://www.autosinnovate.org/posts/papers-reports/Get%20Connected%20EV%20Quarterly%20Report%20Q4.pdf.

3 "Vehicle Miles Traveled by Highway Category and Vehicle Type", Bureau of Transportation Statistics, accessed December 21, 2022, https://www.bts.gov/browse-statistical-products-and-data/freight-facts-and-figures/vehicle-miles-traveled-highway and "Fast Facts on Transportation Greenhouse Gas Emissions", United States Environmental Protection Agency, accessed December 21, 2022, https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions.

4 "President Biden's Bipartisan Infrastructure Law", The White House, accessed Dec 5, 2022, https://www.whitehouse.gov/bipartisan-infrastructure-law/#electricvehicle and The White House, "FACT SHEET: President Biden's Economic Plan Drives America's Electric Vehicle Manufacturing Boom" (September 14, 2022), https://www.whitehouse.gov/briefing-room/statements-releases/2022/09/14/fact-sheet-president-bidens-economic-plan-drives-americas-electric-vehicle-manufacturing-boom/.

5 California Energy Commission New ZEV Sales Dashboard (California ZEV sales data, updated October 18, 2022), https://www.energy.ca.gov/data-reports/energy-almanac/zero-emission-vehicle-

transition and has set especially aggressive EV market goals, targeting 100% ZEV sales by 2030. In 2022, ZEVs accounted for over 26% of new cars sold in the city – despite supply chain disruptions.[6] Moreover, San Francisco has developed many strategies within its Climate Action Plan and Citywide EV Roadmap and local policies to reduce the city's emissions.[7]

ICCT's 2020 San Francisco charging gap analysis found that achieving the city's 100% EV sales goal in 2030 means that more than 170,000 EVs could be on city roads that year, and that a local network of over 5,000 publicly accessible (i.e., public Level 2, DC fast, and workplace chargers) and 80,000 home chargers will be needed to support the EV transition.[8] Policy interventions such as mode-shift from personal vehicles to more sustainable modes (i.e. transit and pedestrian), congestion pricing, and the deployment of residential overnight curbside chargers[9] were shown to reduce these public charging needs significantly. These policy and market developments lead to questions of where to prioritize investing city resources in charging infrastructure that will be increasingly utilized, convenient to access, and will maximize low charging costs for consumers to encourage EV adoption. Market changes could influence a change in how the city invests in EV infrastructure in order to promote EV adoption. This memo investigates the direction of the EV market and potential near-term developments in EV, battery, and charging technologies to inform the type of charging stations needed to support market growth. It finds that charging of all types – home, residential overnight curbside, workplace, public Level 2, and public DC fast – will be critical to providing the necessary geographic coverage, although home and near-home residential overnight curbside are likely to remain the foundation of U.S. charging infrastructure largely due to the consumer cost and convenience benefits that come with it.

Electric vehicle market developments and implications for charging

Ongoing developments in the EV market provide insight into trends for EV adoption and present implications for charging dynamics and charging network build-out priorities and needs. This section examines manufacturing production-side developments, such as EV cost trends, model offerings, and vehicle specifications, as well as charging and battery technology market developments, such as improvements in charging speeds, alternative battery chemistries, and

---

and-infrastructure-statistics/new-zev-sales and "California moves to accelerate to 100% new zero-emission vehicles sales by 2035", California Air Resources Board, updated August 25, 2022, https://ww2.arb.ca.gov/news/california-moves-accelerate-100-new-zero-emission-vehicle-sales-2035.

6 California Energy Commission ZEV and Infrastructure Stats Dashboard (California ZEV sales shares accessed January 2023), https://www.energy.ca.gov/files/zev-and-infrastructure-stats-data?sort=desc&order=Name.

7 City & County of San Francisco, "San Francisco's Climate Action Plan 2021" (2021), https://sfenvironment.org/sites/default/files/events/cap_fulldocument_wappendix_web_220124.pdf and San Francisco Electric Vehicle Working Group, "Proposed Electric Vehicle Roadmap for San Francisco" (2019), https://sfenvironment.org/sites/default/files/fliers/files/sfe_tr_ev-roadmap.pdf.

8 Chih-Wei Hsu, Peter Slowik, Nic Lutsey, *City charging infrastructure needs to reach 100% electric vehicle sales: The case of San Francisco*, (ICCT, Washington, DC: 2020), https://theicct.org/publication/city-charging-infrastructure-needs-to-reach-100-electric-vehicles-the-case-of-san-francisco/.

9 Residential overnight curbside chargers refer to level 1 or 2 charging stations deployed on curbsides in and around residential neighborhoods. The curbside is considered a public good and is not owned by any resident, so chargers would be deployed and maintained by city agencies for use by residents who lack at-home charging access.

battery swapping. Table 1 summarizes our major findings of important EV market developments factors and their impact on charging dynamics and needs. These developments are discussed further in the sections to follow.

Table 1. Key trends in electric vehicle market development and implications for charging needs

Market Development	Charging Implications
Greater model availability across all vehicle classes and decreasing EV manufacturing costs	Lack of model availability and cost have been major barriers to EV adoption. As costs fall and the number of models available proliferate, EV adoption will accelerate and demand for charging will increase
More long-range EV offerings	Longer EV ranges mean that drivers can drive farther before needing a public charger. This can increase the amount of charging that is done at home and near-home chargers
Fast charging costs are much higher than home and Level 2 charging and are likely to remain that way	Home and near-home charging is the most convenient and affordable way to charge and maximize EVs' fuel savings benefits
Continued incremental improvements in battery technology and performance, faster DC fast charging speeds	DC fast charging speeds have increased but do not to rival gas fill up times. Faster charging speeds typically mean higher electricity costs for consumers. Next-generation battery chemistries are in development and are unlikely to be widely commercialized before 2030. Home charging is likely to remain the most convenient and affordable option
Battery swapping faces challenges	Battery swapping unlikely to supplant charging as preferred "fuel" for most of light-duty ZEVs due to underlying economics and technical standardization barriers

Manufacturing and production market developments

Advancements in ZEV technology and the market broadly set the foundation for determining charging infrastructure needs. Improvements in battery technology and procurement processes have allowed for longer range, more efficient ZEVs with faster charge times to be produced in recent years, while costs for battery and non-battery EV components have come down. A 2022 ICCT study found that by 2031, BEVs with up to 350 miles of range across all LDV classes (cars, crossovers, SUVs, and pickups) will have upfront purchase price parity with comparable gasoline vehicles, providing significant tailwinds to EV adoption.[10] The reductions in vehicle price are expected to be largely driven by reduced battery pack costs that fall below $100 per kilowatt-hour by 2030, in-line with the Department of Energy (DOE) Vehicle Technologies Office's (VTO) goals for battery technology development.[11]

10 Peter Slowik, Aaron Isenstadt, Logan Pierce, and Stephanie Searle, *Assessment of electric vehicle costs and consumer benefits in the United States in the 2022-2035 timeframe*, (ICCT, Washington, DC: 2022), https://theicct.org/publication/ev-cost-benefits-2035-oct22/.

11 "Battery, Charging, and Electric Vehicles", U.S. Department of Energy Vehicle Technologies Office, accessed December 22, 2022, https://www.energy.gov/eere/vehicles/batteries-charging-and-electric-vehicles.

In parallel, global automakers' EV investments tally upwards of one trillion dollars, and they have announced or released new EV model offerings across all classes: cars, crossovers, sport utility vehicles (SUV) and light-duty pickup trucks.[12] In 2022, Rivian and Ford released the first commercial battery-electric pickup models, the R1T and the F-150 Lightning, respectively.[13,14] Figure *1* shows a breakdown of the expected number of ZEV product offerings to be available in the 2022-2025 timeframe. At the end of 2021, 60 ZEV models were available in the California market. Based on automaker announcements, 119 models are now expected before model year (MY) 2026, representing a near 100% increase in the number of ZEV models available.[15]

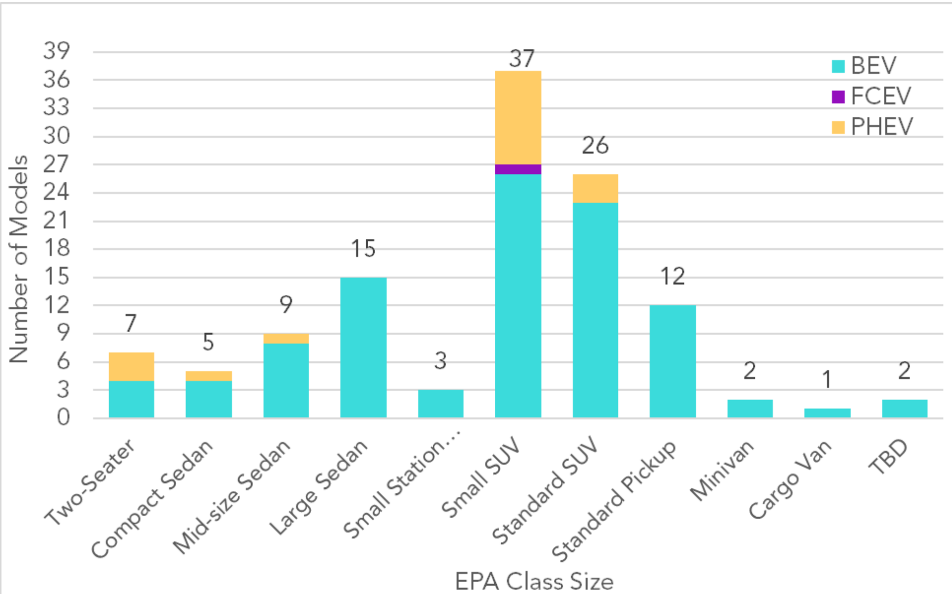

Figure 1. Anticipated ZEV product offerings for model years 2022 through 2025.[16]

Of note are the expected number of new SUV and pickup ZEV offerings. Crossovers (which fall under the EPA's small SUV class size) make up almost half of all light-duty vehicle sales in the US and combined with SUVs and pickup trucks, almost 75%.[17] While most early BEV models have been small cars and sedans (e.g., Nissan Leaf and Tesla Model S), the arrival of more electric SUV and pickup options will appeal to a broader segment of US consumers. More affordable models like the Chevy Bolt EV, Chevy Bolt EUV and Nissan Leaf, which are all under $30,000, and the forthcoming Chevy Equinox EV, which is expected to start at around $30,000,

12 Paul Lienert, "Exclusive: Automakers to double spending on EVs, batteries to $1.2 trillion by 2030," *Reuters*, October 25, 2022, https://www.reuters.com/technology/exclusive-automakers-double-spending-evs-batteries-12-trillion-by-2030-2022-10-21/.
13 "R1T", web page to purchase R1T, Rivian, accessed December 5, 2022, https://rivian.com/r1t.
14 "2022 Ford F-150 Lightning", web page to purchase Ford F-150 Lightning, accessed Decemberr 5, 2022, https://www.ford.com/trucks/f150/f150-lightning-electric-truck/.
15 California Air Resources Board, "Public Hearing to Consider the Proposed Advanced Clean Cars II Regulations, Staff Report: Initial Statement of Reasons" (April 12, 2022), https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/isor.pdf.
16 Ibid.
17 Statista (U.S. light vehicle market in June 2021 and 2022, by segment, updated July 21, 2022), https://www.statista.com/statistics/276506/change-in-us-car-demand-by-vehicle-type/.

will also make EVs more widely accessible.[18] These developments indicate continued progress in overcoming the critical barriers of model availability and vehicle cost, which have long been obstacles to EV mass market adoption, and thus pave the way for greatly continued market growth. In turn, this means that the deployment of sufficient charging infrastructure to support a growing number of EVs on the road is even more pressing.[19]

Automaker EV investments not only promise greater and more affordable model offerings, but also mean greater advancements in EV technology, such as longer range. Electric vehicle ranges have steadily increased over time; in MY2011 the median range for an EV was 68 miles and by MY2021 it had improved to 234 miles.[20] With increasing automaker investments in EVs, it's likely that we will see these trends continue, if not accelerate. Coinciding with automakers' new investments, in MY2022 the number of models with a range of at least 300 miles nearly tripled, increasing from 5 to 14 in one model year after having only grown from one to five over the previous six model years.[21] In cases where home or near-home overnight charging options are available, increasing ranges of EVs reduces the demand for public DC fast charging as drivers are less likely to use their entire battery capacity during daily driving and can recharge when they return home.[22] Table 2 quantifies this relationship showing the home charging share for BEVs and the electric driving share for PHEVs based on their electric range.[23] As shown, on average 150-mile range BEVs can fuel 84% of annual miles with a home charger while a 400-mile BEV can fuel 97%. For a 70-mile range PHEV 79% of annual miles can be powered on electricity, nearly twice that of a 20-mile range PHEV. These dynamics indicate how trends toward longer EV ranges indicate the continued and growing importance of home charging.

Table 2. BEV home charging share and PHEV electric driving share factors.

		Battery electric vehicle		Plug-in hybrid electric vehicle	
		Range	Home charging share	Range	Electric driving share
Electric Range	Short	BEV-150	0.84	PHEV-20	0.40
	Short-mid	BEV-200	0.89	PHEV-30	0.52
	Mid	BEV-250	0.93	PHEV-40	0.62
	Mid-long	BEV-300	0.95	PHEV-50	0.69

18 Angela Symons, "Electric cars are getting cheaper: A sneak peak at GM's sub-€30,000 Equinox EV," *Euronews*, September 13, 2022, https://www.euronews.com/green/2022/09/13/electric-cars-are-about-to-get-more-affordable-a-sneak-peek-at-gms-sub-30000-equinox-ev.

19 Anh Bui, Peter Slowik, Nic Lutsey, *Evaluating electric vehicle market growth across U.S. cities*, (ICCT, Washington, DC: 2021), https://theicct.org/publication/evaluating-electric-vehicle-market-growth-across-u-s-cities/.

20 Department of Energy, "In Model Year 2021 the Electric Vehicle with the Longest Range Reached 405Miles on a Single Charge" (January 10, 2021), https://www.energy.gov/eere/vehicles/articles/fotw-1220-january-10-2022-model-year-2021-electric-vehicle-longest-range.

21 Department of Energy, "Fourteen Model Year 2022 Light-Duty Electric Vehicles Have a Driving Range of 300 Miles or Greater" (August 29, 2022), https://www.energy.gov/eere/vehicles/articles/fotw-1253-august-29-2022-fourteen-model-year-2022-light-duty-electric.

22 Michael Nicholas and Dale Hall. *Lessons learned on early electric vehicle fast charging deployments*, (ICCT, Washington, DC: 2018), https://theicct.org/publication/lessons-learned-on-early-electric-vehicle-fast-charging-deployments/.

23 For BEVs, "home charging share" defines the share of annual VMT that is fueled by a home charger with the rest being supplied by DC fast charger, and for PHEVs "electric driving share" defines the share of annual VMT that is powered by electricity while remaining miles are on gasoline.

	Long	BEV-350	0.96	PHEV-60	0.74
	Long-plus	BEV-400	0.97	PHEV-70	0.79
Source		Duoba (2013)		Bradley and Quinn (2010)	

Charging and battery technology market developments

Figure 2 depicts the EV charging pyramid which ranks the relative importance of different charging types and locations based on early market charging behaviors and preferences. As you go up the pyramid, chargers at each location are less frequently used and/or utilized for shorter periods and have increasing costs. Home charging represents the largest share of charging events as cars are parked for the longest periods at home, allowing plenty of idle time for charging. Drivers without off-street parking park on-street and near-home most of the time, indicating the potential use case for residential overnight curbside charging as a stand-in for home charging.

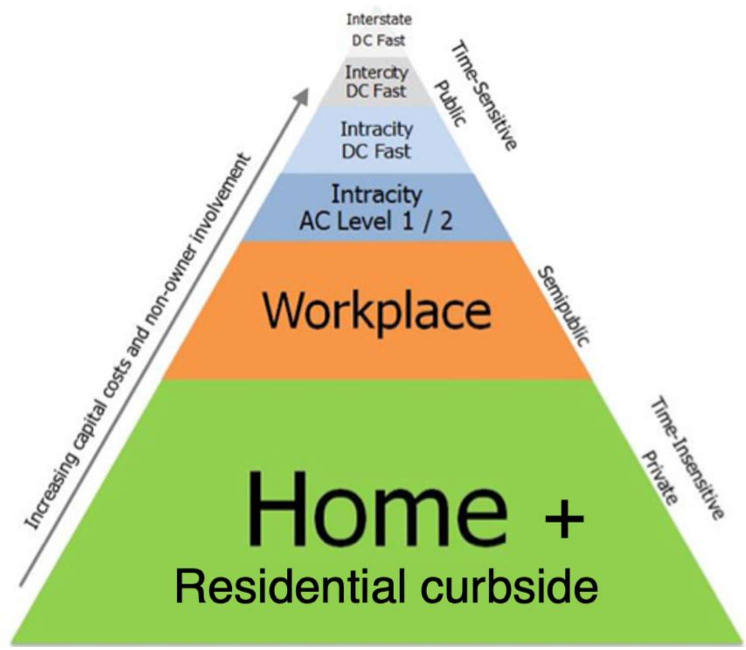

Figure 2. EV charging pyramid, modified to include residential overnight curbside charging; illustrating the relative importance and ranking of different charging types and locations.[24]

As shown by the large green wedge, home and near-home residential overnight curbside are foundational. These chargers typically have the lowest capital costs and electricity costs for EV charging. But home charging alone is insufficient; a charging network of all types – home, workplace, public level 1 and 2, and DC fast – is needed. A diverse infrastructure network that provides the necessary basic geographic coverage is essential to instill confidence in prospective drivers and support early EV market growth. As the EV market grows, more efficient

24 National Academy of Sciences, "Overcoming Barriers to Deployment of Plug-in Electric Vehicles" (2015), https://nap.nationalacademies.org/read/21725/chapter/1.

charging networks can be developed to provide greater charging capacity with fewer chargers per EV.[25]

Table *3* summarizes the different types of chargers and their technical specifications and characteristics available to EVs in the US and the typical applications where they are most commonly used. These include Level 1, Level 2, and DC fast chargers, which typically have a nominal rated power 1-2 kW, 3-19 kW, and 50-350 kW, respectively.

Table 3. Characteristics and specifications of EV charging levels in the United States.

Charging level	Nominal power[26]	Electric vehicle miles of range per hour[a]	Typical application
Level 1	1-2 kW	4-8 miles	Home; using standard household outlet
Level 2	3-19 kW	10-67 miles	Home, workplace, public; in homes appliance outlet can be used, otherwise a hardwired charging station
DC fast charging	50-350 kW	175-1225 miles	Public; charging hubs alongside highways and in cities

[a] Assumes maximum charging power throughout session and EV efficiency of 3.5 miles/kWh

The 8-10 hours cars spend parked overnight means slower level 1 and 2 AC charging is often sufficient to recharge for the next day's driving needs. Additionally, the convenience of not needing to detour to a gas station, and lower "fuel" costs compared to using gas or a public charger, makes charging at home more enticing. For example, the fuel cost per mile of a new 34 mpg car paying $5/gallon is about $0.15 compared to about $0.07 per mile for an EV paying typical PG&E overnight EV home charging rates in San Francisco of $0.24 per kilowatt-hour.[27] Outside of daily travel, EV drivers with home charging will charge using public chargers to add extra range while driving long distances. As the EV market grows, and if home or near-home residential overnight curbside charging is not widely available, a greater number of drivers without the option to charge at- or near-home, especially those living in apartments, will enter the market and be reliant on public charging for their daily driving needs. Greater reliance on public charging comes with higher fueling costs – the cost per kilowatt-hour at public fast charging is typically at least 50% greater than overnight home charging.[28]

Public charging stations are typically level 2, ideally used when parked for an extended period (e.g. at a mall parking lot or overnight in a residential neighborhood), or for DC fast charging (DCFC), usually to support long distance travel because they can provide nearly a full charge in less than an hour. Urban DCFC is a great early transitional technology because a single

25 Nicholas, M., Hall, D., and. Lutsey, N. (2019). Quantifying the electric vehicle charging infrastructure gap across U.S. markets. *ICCT*. https://theicct.org/publication/quantifying-the-electric-vehicle-charging-infrastructure-gap-across-u-s-markets/

26 Level 2 specifications sourced from Joe Wiesenfelder, "What is Level 1, 2, 3 Charging?," *Cars.com*, July 26, 2021, https://www.cars.com/articles/what-is-level-1-2-3-charging-437766/.

27 Electric vehicle (EV) rate plans. (2023). Pacific Gas and Electric. https://www.pge.com/en_US/residential/rate-plans/rate-plan-options/electric-vehicle-base-plan/electric-vehicle-base-plan.page

28 EVgo Fast Charging Pricing. (2023). EVgo. https://www.evgo.com/pricing/

charging station can serve hundreds of EVs, allowing any prospective driver to access an EV regardless of their access to home charging.[29] Planned public and private sector charging investments are largely focused on DCFC. The Biden administration's National Electric Vehicle Infrastructure (NEVI) Formula Program earmarks $5 billion to build a network of chargers alongside interstate highways, and automakers like GM and Mercedes have announced plans to build thousands of public DCFC alongside highways as well as charging hubs in urban centers.[30] These investments will be critical to expanding electric vehicle range and functionality while reducing range anxiety. However, using DC fast charging as a primary option has some drawbacks like user costs, battery degradation, and charging speed relative to gasoline refueling. These are discussed below.

The faster the charger, the more costly a charging session typically is. Idle fees and demand charges can make the price per kilowatt-hour at DCFC stations much greater than for public level 2 charging stations or charging at home. In California, users of Tesla's supercharger network have seen rates increase; up 10 cents from $0.48/kWh to $0.58/kWh during peak hours just in May 2022 (one user reported rates having more than doubled between 2018 and 2022, going from a flat $0.26/kWh fee to $0.58/kWh and $0.29/kWh during peak and off-peak hours, respectively).[31] With greater EV adoption and utilization of DCFC, station operators will be able to split demand charges among more users to help reduce the DCFC prices, but it is unclear if they could ever approach the price of overnight home or near-home Level 1 or Level 2 charging. Many utilities offer time-of-use (TOU) rates to those charging at home which can cut charging prices by half or more during off-peak hours, and this is expected to become more widespread.[32] Users reliant on DCFC can also reduce costs further by charging at off-peak hours, but it is less convenient to have to leave home to find a DCFC station late at night or early in the morning than to leave the car parked and plugged in overnight. Even still, a 2022 ICCT study found that drivers who rely on public DCFC are expected to pay between $1,360 and $3,200 more in electricity costs over a 6-year ownership period than they would relying on slower home charging.[33]

---

29 Michael Nicholas and Dale Hall, *Lessons learned on early electric vehicle fast charging deployments*, (ICCT, Washington, DC: 2018), https://theicct.org/publication/lessons-learned-on-early-electric-vehicle-fast-charging-deployments/ and discussions with Mike Nicholas (CEC).

30 Emma Newburger "All 50 states get green light to build EV charging stations covering 75,000 miles of highways," *CNBC*, September 27, 2022, https://www.cnbc.com/2022/09/27/ev-charging-stations-on-highways-dot-approves-50-states-plans.html, Scooter Doll, "GM announces new nationwide DC fast charging network with Pilot Co. and EVgo," *Electrek*, July 14, 2022, https://electrek.co/2022/07/14/gm-dc-fast-charging-network/, and Andrew J. Hawkins, "Mercedes-Benz and ChargePoint are going to install thousands of EV fast chargers in the US," *The Verge*, January 5, 2023, https://www.theverge.com/2023/1/5/23538898/mercedes-benz-chargepoint-ev-charging-stations-build.

31 Iqtidar Ali, "Tesla owners in California feel uneasy as Supercharging costs are constantly on the rise," *Teslaoracle.com*, May 15, 2022,https://www.teslaoracle.com/2022/05/15/tesla-owners-in-california-uneasy-as-supercharging-costs-are-on-the-constant-rise/.

32 Alameda, https://www.alamedamp.com/393/TOU-Time-of-Use-Rate-for-EV-Owners, and PG&E https://www.pge.com/en_US/residential/rate-plans/rate-plan-options/electric-vehicle-base-plan/electric-vehicle-base-plan.page, conversations with Mike Nicholas, incorporated TOU rates in CEC IEPR https://www.energy.ca.gov/data-reports/reports/integrated-energy-policy-report/2021-integrated-energy-policy-report.

33 Peter Slowik, Aaron Isenstadt, Logan Pierce, and Stephanie Searle, *Assessment of electric vehicle costs and consumer benefits in the United States in the 2022-2035 timeframe*, (ICCT, Washington, DC: 2022), https://theicct.org/publication/ev-cost-benefits-2035-oct22/.

Beyond price, current battery technology limits the potential for DCFC to outright replace Level 1 and Level 2 AC charging as preferred and primary charging methods. Battery degradation and subsequent loss of range can be a challenge, especially for BEVs with NMC (nickel-manganese-cobalt) and NCA (nickel-cobalt-aluminum) battery chemistries that have especially high DC fast charging usage. The process of charging and discharging a battery wears it down reducing capacity, and regular use of DCFC has been shown to accelerate this process compared to AC charging.[34] The extent to which technological advancements will minimize battery degradation from frequent DC fast charging use are unclear. The ACCII regulation put forward by the California Air Resources Board (CARB) requires that automakers ensure BEVs maintain at least a 70% battery state of health for 8 years or 100,000 miles through MY2030, indicating that battery degradation will be an important issue in the near term.[35]

LFP (lithium-iron-phosphate) batteries used in a handful of models have shown potential to enable lower costs and minimize degradation.[36] However, this chemistry is less energy dense, meaning less range and more frequent charging for a given battery size. Faster charging speeds could make this less of an issue, and efforts to optimize EV battery technology have produced gradual improvements in DCFC speeds with EVs being able to add around 100 miles of range in 15 minutes to almost 150 miles for the best-in-class models, over the last three model years.[37] DOE's VTO has goals to double this rate to 300 miles in 15 min, meanwhile charging companies are increasing production and deployment of "ultra-fast" 350 kW chargers in anticipation of EVs that have the technical specifications to charge at 350 kW.[38] Of the EVs on the market today, only the GMC Hummer EV is capable of charging at 350 kW.[39] Other luxury vehicles like the Lucid Air and Porsche Taycan come close at 300kW and 270kW, respectively, while more affordable models like the Chevy Bolt and Hyundai Kona EV peak around 50 kW.[40] Thus, the potential for widespread ultra-fast charging appears quite limited based on the capability of EV models on the market as of 2022.

---

34 Dave Nichols, "EV Battery Maintenance Best Practices," *GreenCars*, September 2022, https://www.greencars.com/post/why-dc-fast-charging-reduces-ev-battery-life.

35 California Air Resources Board, "Public Hearing to Consider the Proposed Advanced Clean Cars II Regulations, Staff Report: Initial Statement of Reasons" (April 12, 2022), https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/accii/isor.pdf.

36 Henry Man, "What are LFP, NMC, NCA Batteries in Electric Cars?", *Zecar.com*, July 18, 2022, https://zecar.com/post/what-are-lfp-nmc-nca-batteries-in-electric-cars#Other%20battery%20developments.

37 Christian Daake, Marian Cammerer, and Markus Hackmann, "Comparison of the fast charging capabilities of electric vehicles," (P3, July 18, 2022), https://www.p3-group.com/en/p3-charging-index-comparison-of-the-fast-charging-capability-of-various-electric-vehicles-from-a-users-perspective_07-22/.

38 "Battery, Charging, and Electric Vehicles", U.S. Department of Energy Vehicle Technologies Office, accessed December 22, 2022, https://www.energy.gov/eere/vehicles/batteries-charging-and-electric-vehicles, Mark Kane, "Tritium Opens A New DC Fast Charger Factory In Tennessee," *InsideEVs*, August 24, 2022, https://insideevs.com/news/606273/tritium-opens-fast-charger-factory-tennessee/.

39 John Beltz Snyde, "Fastest-charging electric cars of 2022," *Autoblog*, August 5, 2022, https://www.autoblog.com/article/fastest-charging-electric-cars/?guccounter=1&guce_referrer=aHR0cHM6Ly93d3cuZ29vZ2xlLmNvbS8&guce_referrer_sig=AQAAAEVpacBYkWWjqKtwfIcLZZOGWIRpvM1PDopclEnvjR4h3JtFhadIOJ8spSvXh6usMHVSCL9HugPNypa3BAJioK5qPbZHHBBJ6_WtCJu1BO1lWmyPKW8A_vgPhUDVn7EOGSORdmCf-hxxr9z2OH4mE50z_CpoTb2fBKON-81-MrIX.

40 Ibid and Liz Najman, "Fastest Chargin EVs in 2022," *Recurrent*, June 3, 2022, https://www.recurrentauto.com/research/fastest-charging-evs.

Ultra-fast DCFC requires a premium battery management system (BMS) that can monitor the battery's temperature and maintain its health during charging, which adds to the cost of the vehicle. For DCFC to become the primary method of charging for most EV drivers will likely require widespread improvement to the specifications of the BMS in EVs at an affordable price and potentially alternative battery chemistries than what is currently on the market. Next-generation solid-state battery technology, which could potentially solve issues with battery degradation, improve energy density, and increase charging speeds, is being developed and early prototypes have been delivered to automakers for testing, but the technology is unlikely to be widely commercialized before 2030.[41] Even then, charging an EV is not expected to become as fast as filling up a gasoline car, and faster charging times will mean greater costs to consumers.[42] Based on limitations, it is likely that overnight slow AC charging near- or at-home will remain the most affordable and convenient option for EV drivers.

A potential alternative charging solution that could significantly reduce "refuel" times is battery swapping, but this technology also faces key challenges such as a lack of standardization in battery configurations and high capital and user costs.[43] Battery swapping replaces a depleted battery with a fully charged one in 5-10 minutes. Currently batteries differ in size and shape between models which would limit which stations drivers could use. Standardization of batteries across the industry appears unlikely as automakers look to vertically integrate battery production.[44] Cost also remains a challenge; San Francisco battery swapping startup Ample is reported to be working toward offering battery swapping that is "as fast as cheap, and as convenient as gas".[45] If electric vehicle charging is the same price as gasoline, their economic benefits and the consumer value proposition will be diminished by thousands of dollars. The extent to which consumers will be willing to make this tradeoff is unclear. As charging times decrease, there will be diminishing benefits to "refueling" time for battery swapping making it unclear if the technology will supplant charging in substantial volume long-term. Nevertheless, there may be a potential use-case for battery swapping in limited specific applications like medium- and heavy-duty (MHDV) fleets, where hundreds or thousands of the same vehicle allow for a default battery configuration. This potential is reflected in Ample's approach, where the company is focused on modular batteries and fleets.[46]

Reflections

---

41 Scooter Doll, "QuantumScape ships first batch of energy dense, 24-layer solid-state batteries to EV automakers," *Electrek*, December 20, 2022, https://electrek.co/2022/12/20/quantumscape-ships-first-24-layer-solid-state-batteries-ev-automakers/ & "Solid-state battery: The Holy Grail in battery research", Electronica, accessed December 5, 2022, https://electronica.de/en/newsroom/industry-portal/detail/solid-state-battery-the-holy-grail-in-battery-research.html.

42 Jim Motavalli, "How Solid-State EV batteries May Lick the Fast-Charging Degradation Problem", *Autoweek*, May 10, 2022,https://www.autoweek.com/news/a39946624/solid-state-ev-batteries-fix-fast-charging-degradation-problem/.

43 Marie Rajon Bernard, Alexander Tankou, Hongyang Cui, and Pierre-Louis Ragon, *Charging solutions for battery-electric trucks*, (ICCT, Washington, DC: 2022), https://theicct.org/publication/charging-infrastructure-trucks-zeva-dec22/.

44 Julia Bush, "Automakers Invest Billions in North American EV and Battery Manufacturing Facilities," (Center for Automotive Research, July 21, 2022), https://www.cargroup.org/automakers-invest-billions-in-north-american-ev-and-battery-manufacturing-facilities/.

45 Ample (2023). Retrieved from https://twitter.com/teamample

46 Pettitt, J. (2021, May 29). Why battery swapping may finally become a part of EV charging infrastructure in the U.S. *CNBC*. https://www.cnbc.com/2021/05/29/how-ample-is-bringing-battery-swapping-to-the-us.html.

Reduced battery and vehicle technology costs, continued technological advancements, and supporting policy actions are driving continued EV market growth, and with it come the prospects for greatly expanded access to a broader set of consumers. Electric vehicle uptake and charging infrastructure deployment grow in parallel, and a comprehensive charging ecosystem of all types – home, residential overnight, workplace, public Level 2, and public DC fast – is needed to support widespread adoption and allow anyone to get an EV and charge reliably.

Where EV drivers charge has important implications on cost and convenience. For DC fast charging in particular, significantly higher capital, installation, and electricity costs, technological limitations for how fast vehicles can charge, and heightened concerns about battery degradation from frequent use make DCFC as a primary charging option less than desirable. In fact, EV drivers that rely on public fast charging for all of their energy needs are expected to pay about $1,360 to $3,200 more in electricity costs over a 6-year period, and potentially emerging alternative charging options like battery swapping appear to cost even more. Slower overnight home and near-home charging is the most convenient and affordable charging option and better for long-term battery health.

As the EV market expands beyond early adopters to the majority market, there will be a greater number of consumers without off-street parking such as those living in multifamily housing that will be reliant on charging options that are different than traditional off-street home charging that has been common among early adopters. Low-cost residential charging at the curb can effectively serve as home charging for many consumers and expand access to the economic benefits that most early adopters of EVs have enjoyed and minimize reliance on charging away from home. Further research about the relative costs, benefits, and usage of different charging options is needed to understand potential tradeoffs and inform cost-effective infrastructure planning.