CRC Report No. SM-CR-9

ASSESS THE BATTERY-RECHARGING AND HYDROGEN-REFUELING INFRASTRUCTURE NEEDS, COSTS AND TIMELINES REQUIRED TO SUPPORT REGULATORY REQUIREMENTS FOR LIGHT-, MEDIUM-, AND HEAVY-DUTY ZERO-EMISSION VEHICLES

EXECUTIVE SUMMARY

for

Final Report

September 2023

COORDINATING RESEARCH COUNCIL, INC.
5755 NORTH POINT PARKWAY • SUITE 265 • ALPHARETTA, GA 30022

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Infrastructure Assessment Objectives

- Anticipated surge in ZEVs across the country
- Infrastructure needs to support ZEV adoption
- Technology mix (BEV, FCEV, PHEV)
- Current gaps to accommodate ZEV surge
- Infrastructure hardware and installation costs* and buildout timelines
- Impact on electricity grid and hydrogen production

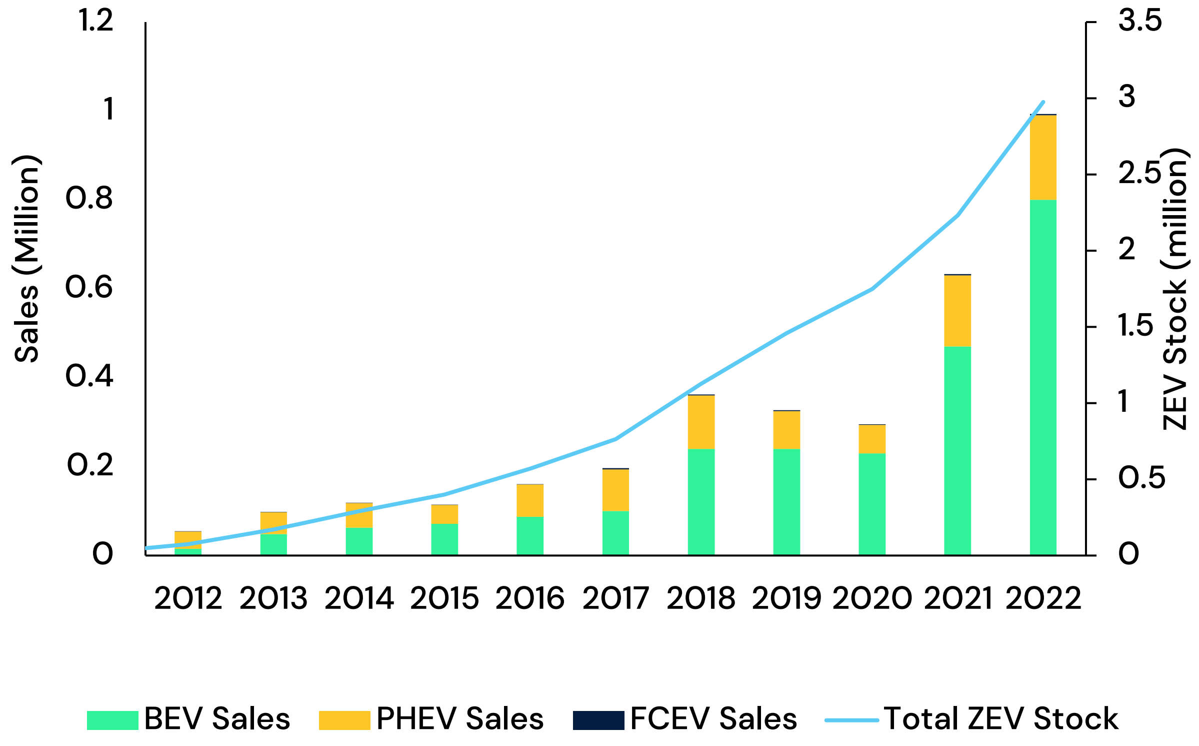
*Cost estimates for BEV charging infrastructure include EVSE hardware and installations, while utility upgrades, land acquisition, and other soft costs are not quantified. Cost estimates for FCEV refueling infrastructure include refilling station compressors/boil off management and retail site distribution pumps, while costs associated with hydrogen production and distribution such as electrolysis unit, compression or liquefaction unit, distribution pipeline, compressed hydrogen delivery trucks or purification units are not quantified.

Background and Motivation

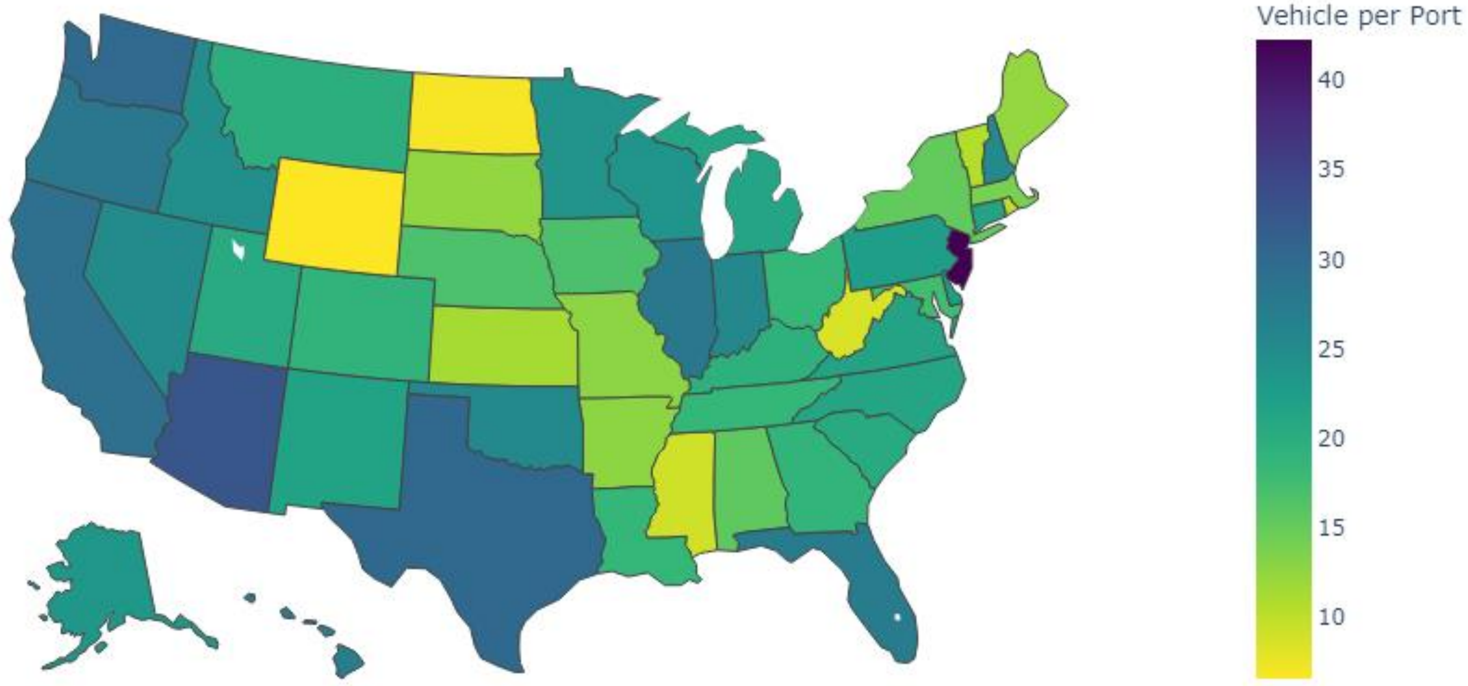
Recently Adopted and Upcoming Regulations

- CARB Advanced Clean Cars II
- CARB Advanced Clean Trucks
- CARB Advanced Clean Fleets
- EPA Phase-3 Proposed Standards
- EPA Proposed Multi-Pollutant Standards

U.S. ZEV sales and total stock in the last decade



Currently EV-per-port (public) ratio in the U.S.



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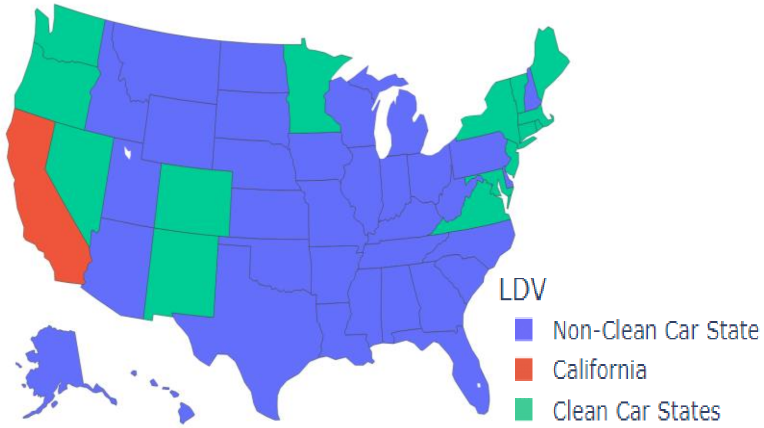
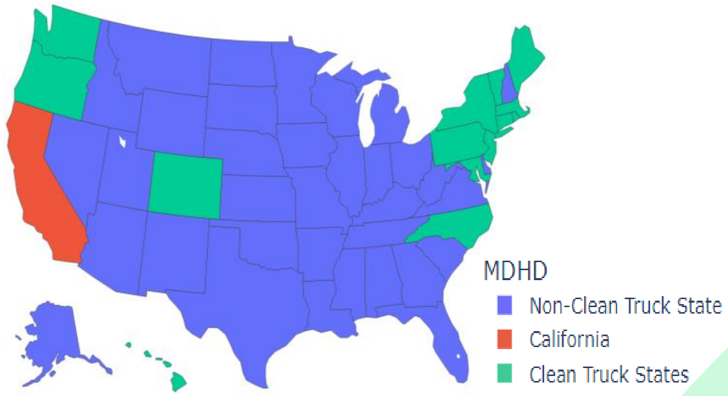
Overview of Methodology and Assumptions

ZEV Adoption Trends and Fleet Modeling Approach

ZEV Adoption Scenario by State and Weight Class

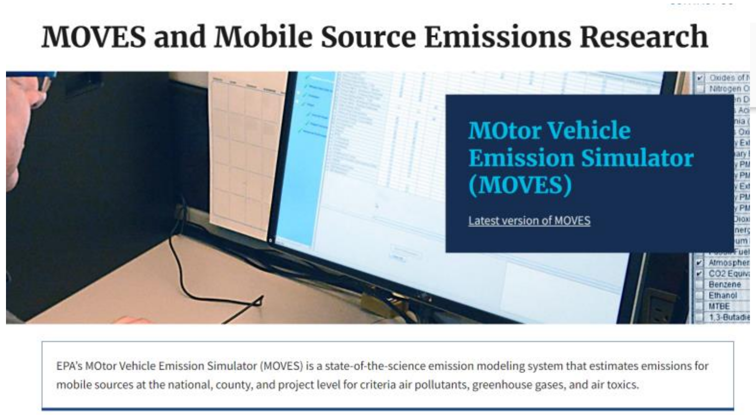


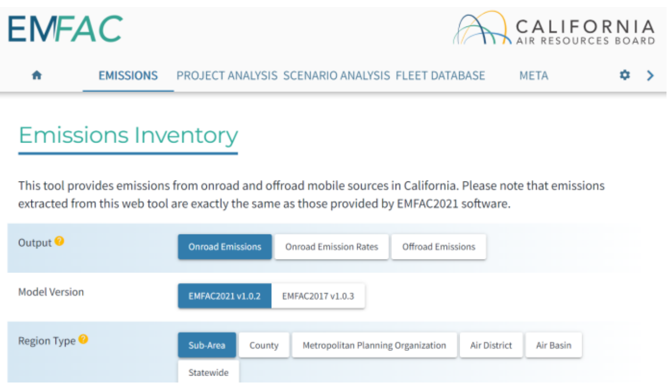


Electricity and hydrogen demand from ZEV adoption

ZEV adoption curves, aligned with the regulatory requirements and regional targets

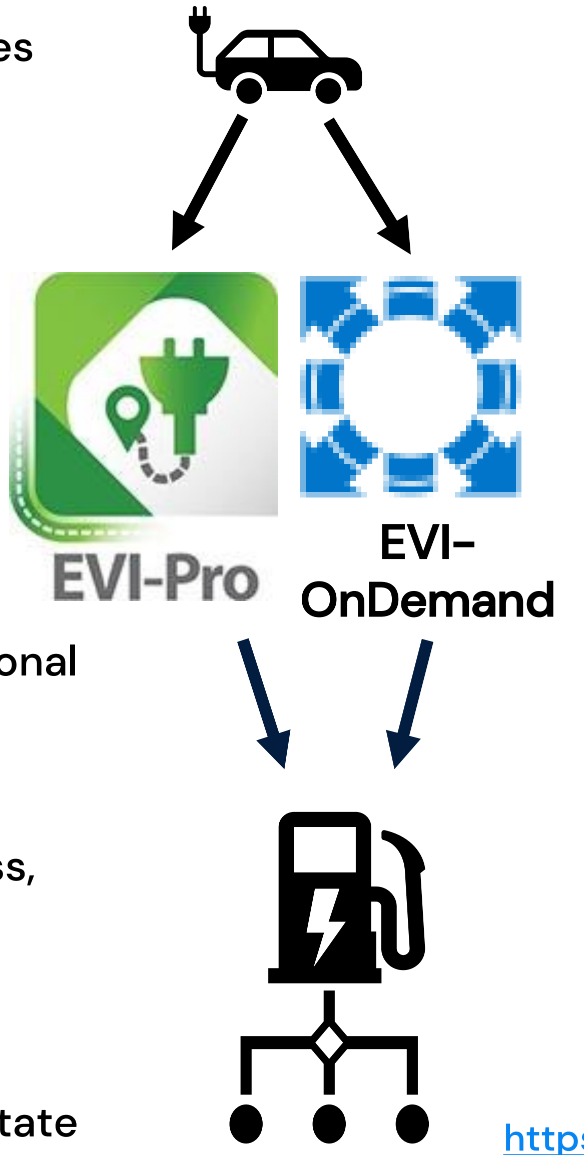
“Business-as-usual” vehicle stock and sales

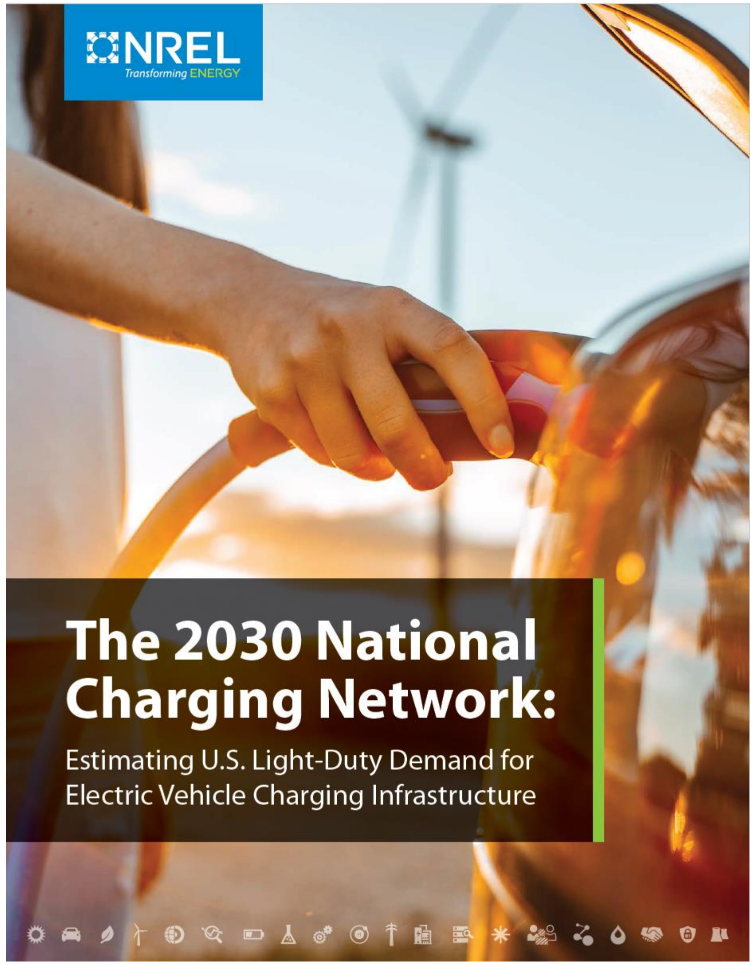




Infrastructure Needs Assessment Methodology – LD PEV

- **NREL's Electric Vehicle Infrastructure Projection Tool (EVI-Pro)**
  - Well suited for personally owned, light-duty vehicles, including vehicles driven for transportation network companies.
  - This analysis includes passenger car and passenger truck from MOVES/CO2Sight modeling.
  - EVI-Pro projects number of chargers by type and category:
    - Single Family
    - Shared Private (multi-unit dwelling, office, etc.)
    - Public Level 2
    - Public DCFC
- **NREL's EVI-OnDemand**
  - Fast charging needs for ride-hailing electrification
  - Also used to account for charging needs from road trips and interregional trips
  - Public DCFCs
- Key driver for PEV charging network is the percent of home charging access, which can vary by year and state
  - NREL is aware that there is not a rigorous approach to determining national averages for home charging access*.
- **Approach:** Aggregate total passenger car and passenger truck counts by state and year, determine home charging access percent, offer input to EVI-Pro and EVI-OnDemand for expected charging needs and distribution.





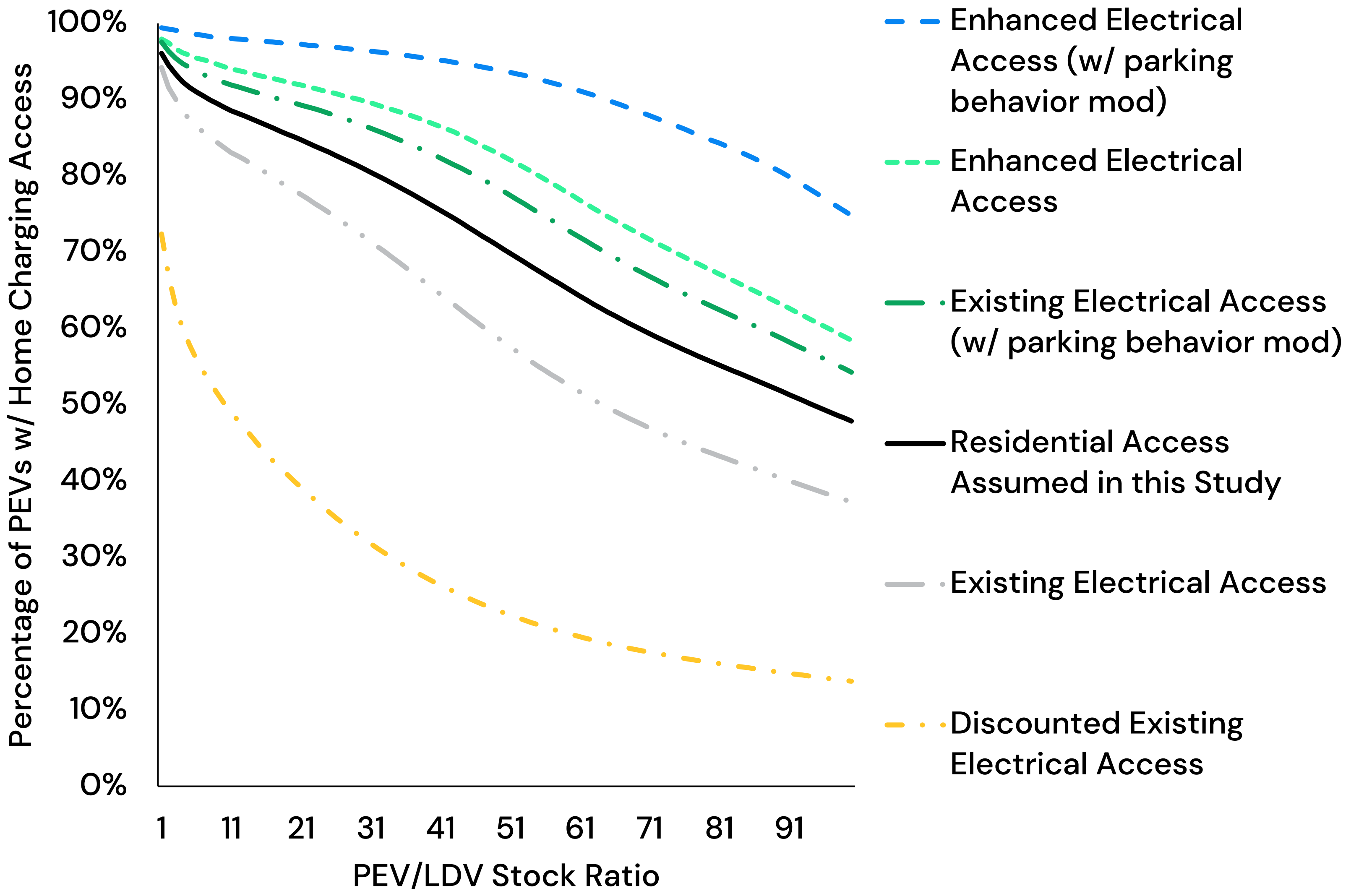
https://www.nrel.gov/docs/fy23osti/85970.pdf
https://afdc.energy.gov/evi-pro-lite

*Source: Personal communication with EVI-Pro technical leads, July 17, 2023.

LD PEV Residential Charging Access Assumptions

- NREL's study on residential charging potential by housing type considers several scenarios based on residential parking and electrical survey.
  - Existing Electrical Access: Residential charging is possible so long as vehicle is currently parked near electrical access.
  - Enhanced Electrical Access: Residential charging as available if a vehicle is parked at a location where there is currently or is possible for electrical access to be installed.
  - Existing Electrical Access with Parking Behavior Modification: Vehicle is regularly parked somewhere else but can be moved to residence with electrical access.
- The project team developed a new home charging access scenario using a 50%-50%* combination of the "Existing Electrical Access" and the "Enhanced Electrical Access".

- Home charging access can be determined based on the PEV:LDV stock ratio to drive EVI-Pro's charging needs distribution.



There's No Place Like Home: Residential Parking, Electrical Access, and Implications for the Future of Electric Vehicle Charging Infrastructure (nrel.gov)

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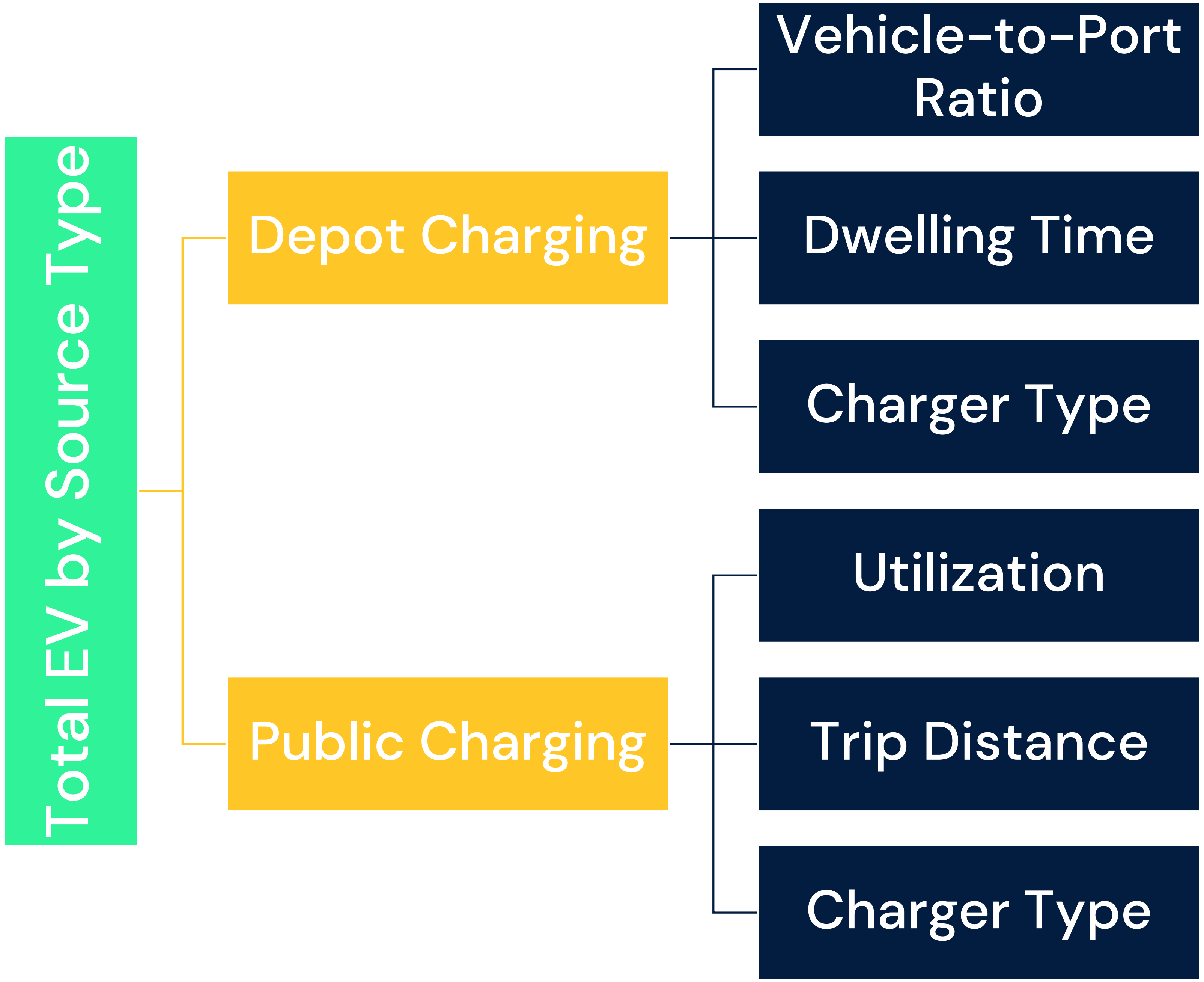
**Source*: Personal communication with EVI-Pro technical leads, August 16, 2023.

Infrastructure Needs Assessment Methodology – MDHD PEV

- The project team built a new model that evaluates the charging needs for light commercial trucks and MDHD BEV fleets.
- The model considers the operational characteristics of vehicles across the nation by source type, including daily operation hours, dwelling time, duty cycles, etc.



MDHD PEV Charging Access and Type Assumptions

	Operation Days	Daily Operation (Hours)	Depot	Depot Vehicle to Port	Public	Public Charger Level (kW)	Public Charger Utilization
Combination Long-haul Truck	312	9.77	0.1	1 : 1	0.675	350	0.2
					0.225	1000	0.2
Combination Short-haul Truck	312	6.5	0.59	1 : 1	0.41	350	0.2
Light Commercial Truck	312	2.81	0.72	2 : 1	0.28	150	0.2
Other Buses	292	8.73	1	1 : 1	0	N/A	N/A
Refuse Truck	312	5.68	1	2 : 1	0	N/A	N/A
School Bus	327	2.45	1	2 : 1	0	N/A	N/A
Single Unit Long-haul Truck	312	5.18	0.59	2 : 1	0.41	150	0.2
Single Unit Short-haul Truck	312	3.42	0.72	2 : 1	0.28	150	0.2
Transit Bus	327	9.06	1	1 : 1	0	N/A	N/A

- Depot vs. Public charging determined from CARB ACT Large Entity Reporting: Vehicles Regularly Parked at the Home Base > 8 hr/day.
- Vehicle-to-Port ratio set to 1:1 if daily operation hours is longer than 6 hours; otherwise, ratio set to 2:1.
- For long-haul tractors, telematics data suggests 25% trips are slip-seat operations, meaning the truck is driven for more than 700 miles or 16 h without stopping for a break of 4 h or longer. Therefore, 25% of Combination Long-haul Trucks that require public charging access are assumed to use the ultrafast Megawatt Charging System (MCS) and the rest will need DCFC 350 kW.
- Depot charger type is determined using daily charging demand/charging cycle (8 hrs).
- Public charger type is consistent with OEM recommendation; battery acceptance rate is assumed to be the same as charger power output.
- Public charger utilization is assumed to be 20% constant, instead of ramping up as a mature market does not necessarily indicate a utilization higher than 20%.

ICF Fleet Assessment Tool – EVSE Hardware and Installation Cost Assumptions

- ICF's Fleet Assessment Tool sources average EV charger hardware and installation costs by type.
  - Average DCFC installation cost calculated as the average between ICCT 2019, NREL 2020, and RMI 2020 estimates
- ICCT, RMI, and EPRI studies suggest that hardware and installation costs of dual port chargers are 10% lower .
- 2MW cost cited from the Atlas study.

Max of kW Range	Charging Level	kW Range	Average Hardware Cost - Networked	Average Installation Cost – Networked	Total Hardware & Installation Cost - Networked
6	L2	L2 (3-6 kW)	$2,500	$3,500	$6,000
8	L2	L2 (6-8 kW)	$3,000	$3,500	$6,500
11	L2	L2 (8-11 kW)	$3,500	$3,500	$7,000
15	L2	L2 (12-15 kW)	$4,000	$3,500	$7,500
19	L2	L2 (15-19 kW)	$4,500	$3,500	$8,000
50	DCFC	DCFC (50 kW)	$35,800	$28,100	$63,900
150	DCFC	DCFC (150 kW)	$100,000	$42,200	$142,200
350	DCFC	DCFC (350 kW)	$150,000	$61,600	$211,600
2000	MW	2 MW	$600,000	$130,000	$730,000

ICF Fleet Assessment Tool Single Port Hardware and Installation Costs

Sources:
ICF 2022: https://www.icf.com/insights/transportation/electric-vehicle-charging-infrastructure-costs
NREL 2020: https://www.cell.com/action/showPdf?pii=S2542-4351%2820%2930231-2
RMI 2020: https://rmi.org/wp-content/uploads/2020/01/RMI-EV-Charging-Infrastructure-Costs.pdf
ICF 2019: https://www.caletc.com/assets/files/ICF-Truck-Report_Final_December-2019.pdf
ICCT 2019: https://theicct.org/sites/default/files/publications/ICCT_EV_Charging_Cost_20190813.pdf
RMI 2014: https://rmi.org/pulling-back-veil-ev-charging-station-costs/
EPRI 2013: https://www.epri.com/research/products/000000003002000577
DOE 2015: https://afdc.energy.gov/files/u/publication/evse_cost_report_2015.pdf
WCCTI 2020, https://www.westcoastcleantransit.com/
ATLAS 2021, https://atlaspolicy.com/u-s-medium-and-heavy-duty-truck-electrification-infrastructure-assessment/
Clipper Creek: https://store.clippercreek.com/level2

Hydrogen Station Capacity- Methodology Assumptions

- Hydrogen refueling stations will first start with low and mid capacity, and then gradually phase-in with high capacity

Year	Station Capacity (CA LD) (kg/day)	Station Capacity (CA HD) (kg/day)	Station Capacity (non-CA HD) (kg/day)
2020	200	900	
2024	350	1,200	
2026	600	1,600	
2028	900	2,000	
2030	1,200	3,000	1,200
2032	1,600	4,000	1,600
2034	2,000	5,000	2,000
2036			3,000
2038			4,000
2040			5,000

- Once a category of station capacity is phased-in, <u>*5%*</u> natural growth rate is assumed, and the growth stops once the max station capacity is reached (e.g. 2034 for CA LD and HD, and 2040 for non-CA HD)

- If multiple categories compete market shares, the installation of stations with higher capacity has higher priorities than lower ones

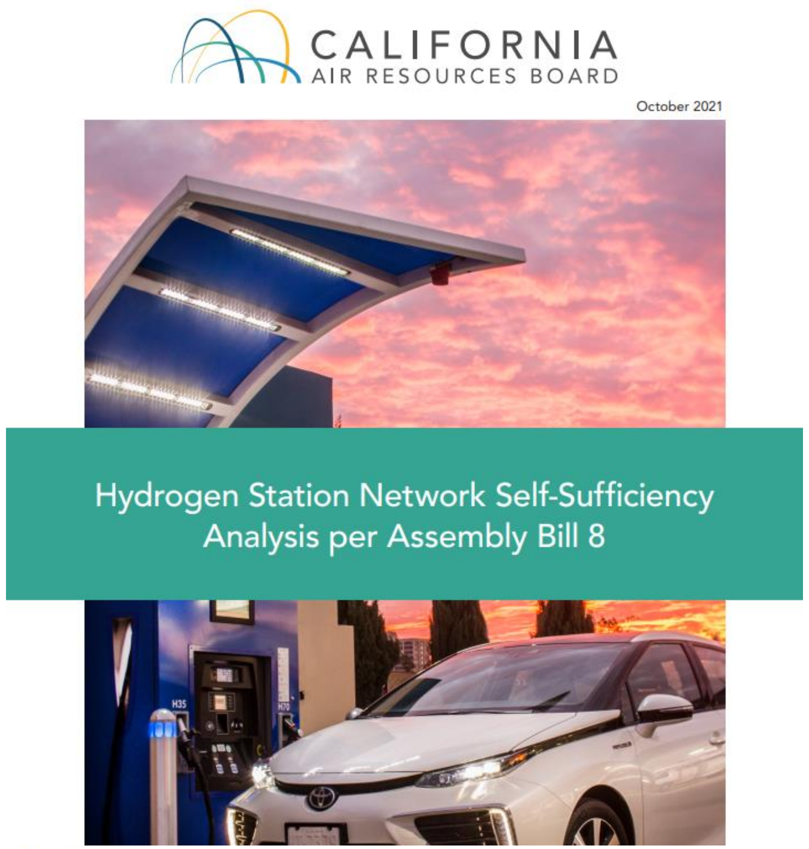
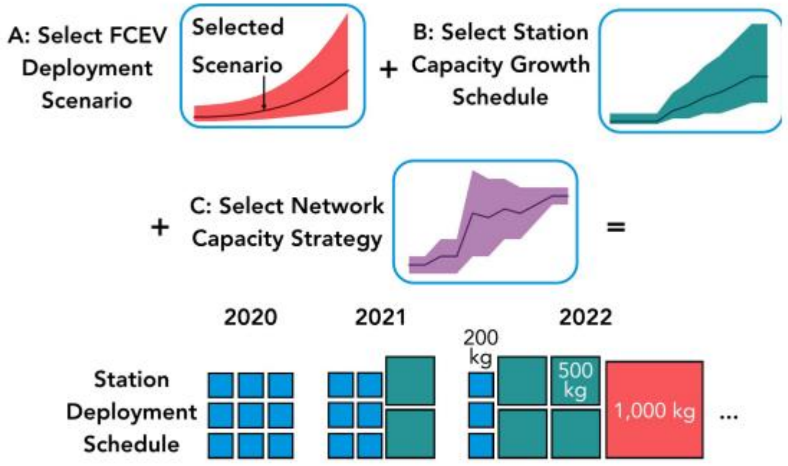
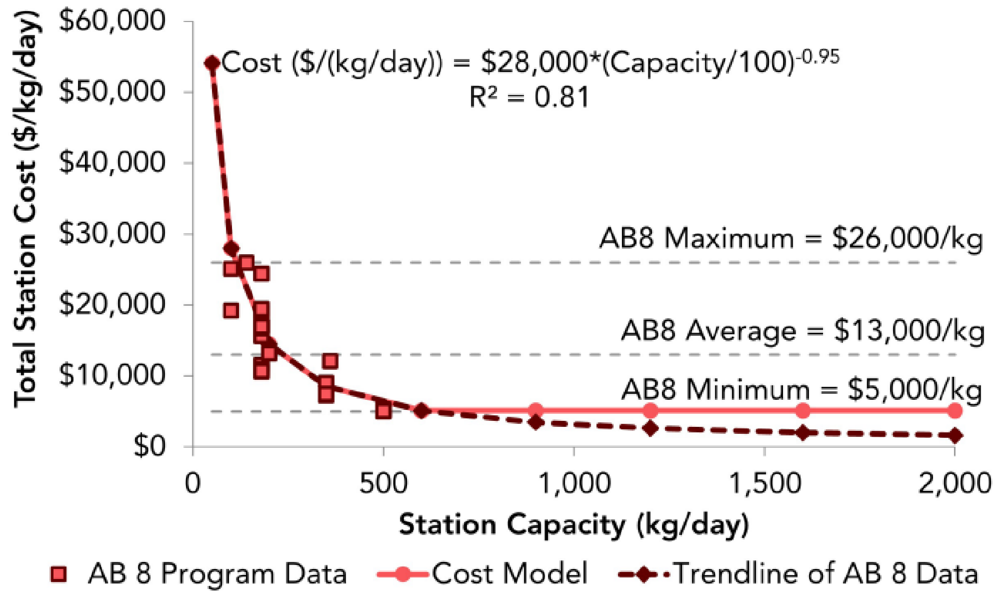


FIGURE 16: DEMONSTRATION OF DEFINING STATION DEPLOYMENT SCHEDULE

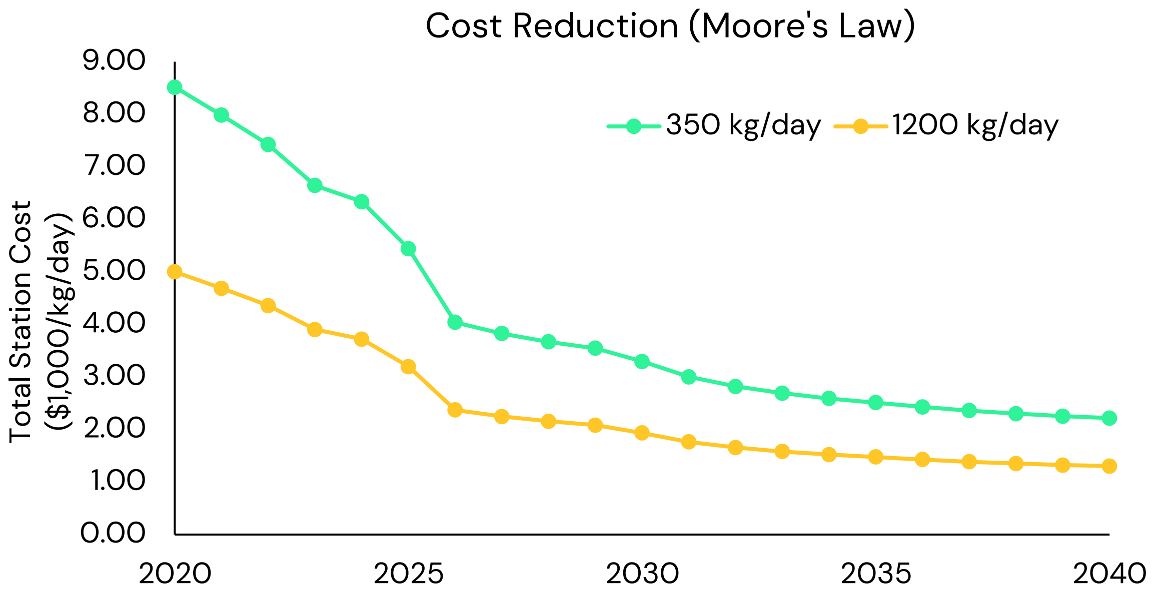


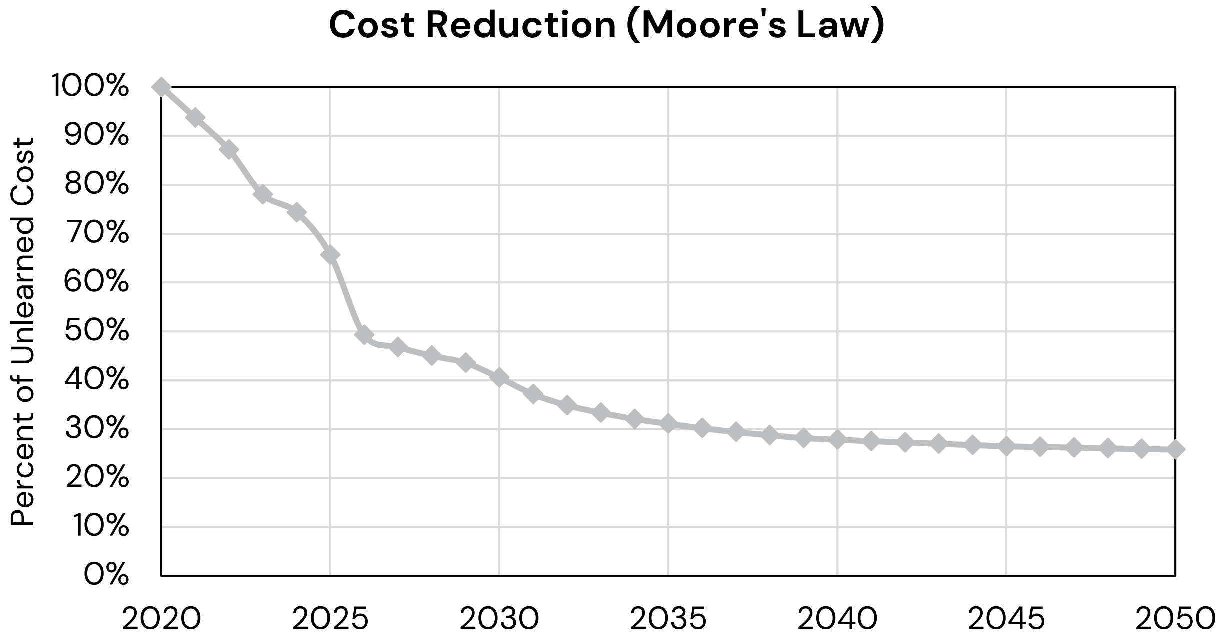
Reference 1: https://ww2.arb.ca.gov/sites/default/files/2021-10/hydrogen_self_sufficiency_report.pdf
Reference 2: https://www.sandag.org/-/media/SANDAG/Documents/PDF/projects-and-programs/innovative-mobility/clean-transportation/regional-medium-duty-heavy-duty/md-hd-zev-needs-assessment-report-2023-01-01.pdf

Hydrogen Infrastructure Station Installation Cost – Assumptions



Note: Does not include 2 outliers (verified by Grubbs' test at 0.05 significance) , 1 Null (Incomplete) data point, nor mobile fueler



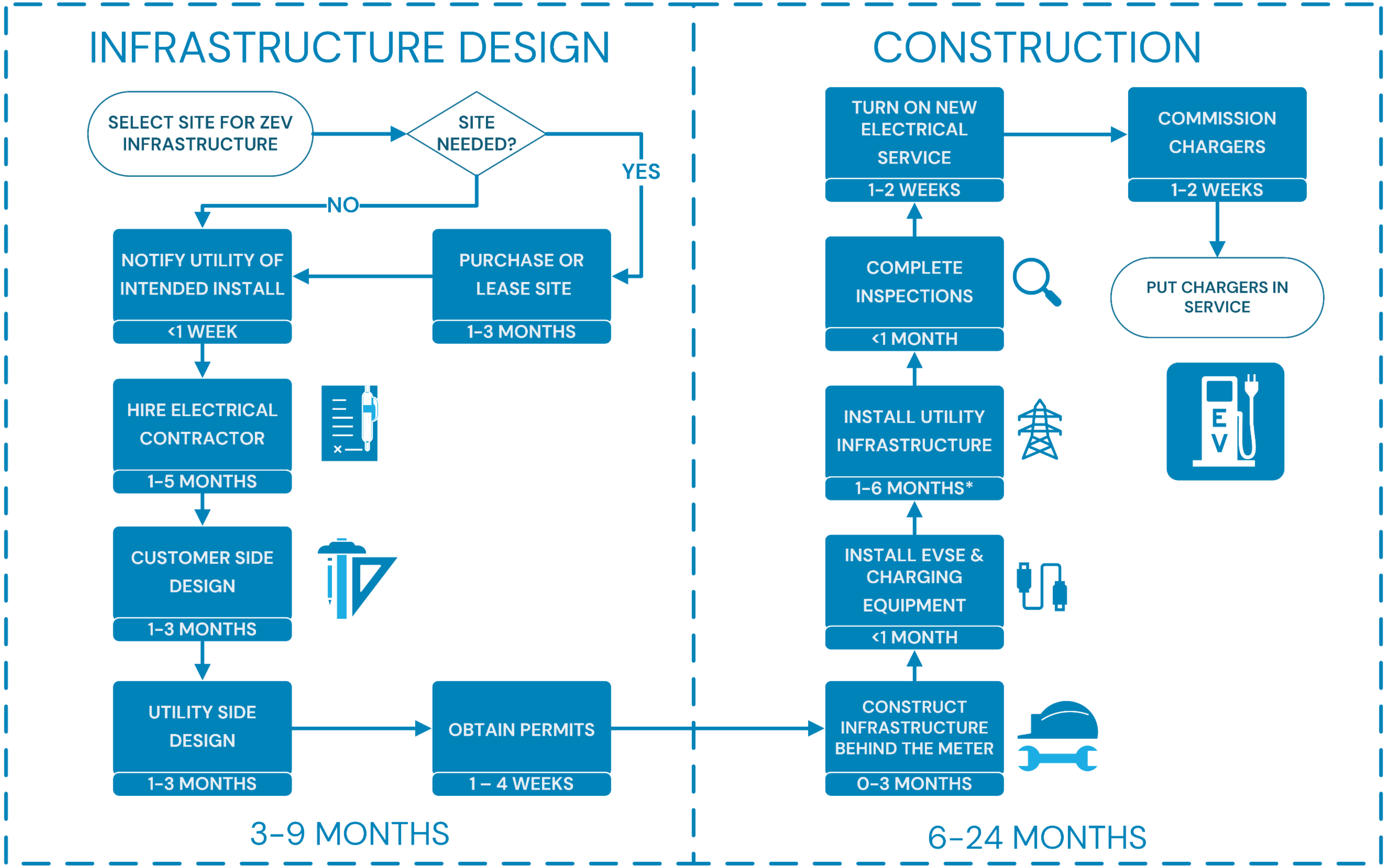


Project	Daily Capacity	Refueling Station Specs	Liquid or Gaseous	Estimated Costs (Total funding)
Shell[41]	5000 kg	3X350 bar and 3X750 bar fueling positions	Gaseous fuel delivery	$6.8M
Orange County Transportation Authority	4,536 kg	350 bar	Not Available	$6M
First Energy's NorCal Zero station	1,610 kg	700 bar	Liquid hydrogen delivery	$8.2M
Alameda-Contra Costa Transit -Emeryville Facility[42]	1,750 kg	Not Available	Not Available	$4.4M
Average cost per dispensed capacity (daily capacity)				**~$2600/kg**

Reference 1: https://ww2.arb.ca.gov/sites/default/files/2021-10/hydrogen_self_sufficiency_report.pdf
Reference 2: Feasibility study of EPA NPRM Phase 3 GHG standards for Medium Heavy-Duty Vehicles (Truck and Engine Manufacturers Associations)

Charging Infrastructure Development Timeline – Review

- Non-residential EV charger projects usually take 1-2 years from start to finish – we conservatively estimate that at least two years of lead time will be needed.
- Locations such as public chargers with large numbers of DCFCs or MCS typically have timelines extending well above one year, up to several years depending on the utility side changes needed.



* Utility installation time can take 1-7 years if substation upgrades or replacement is needed

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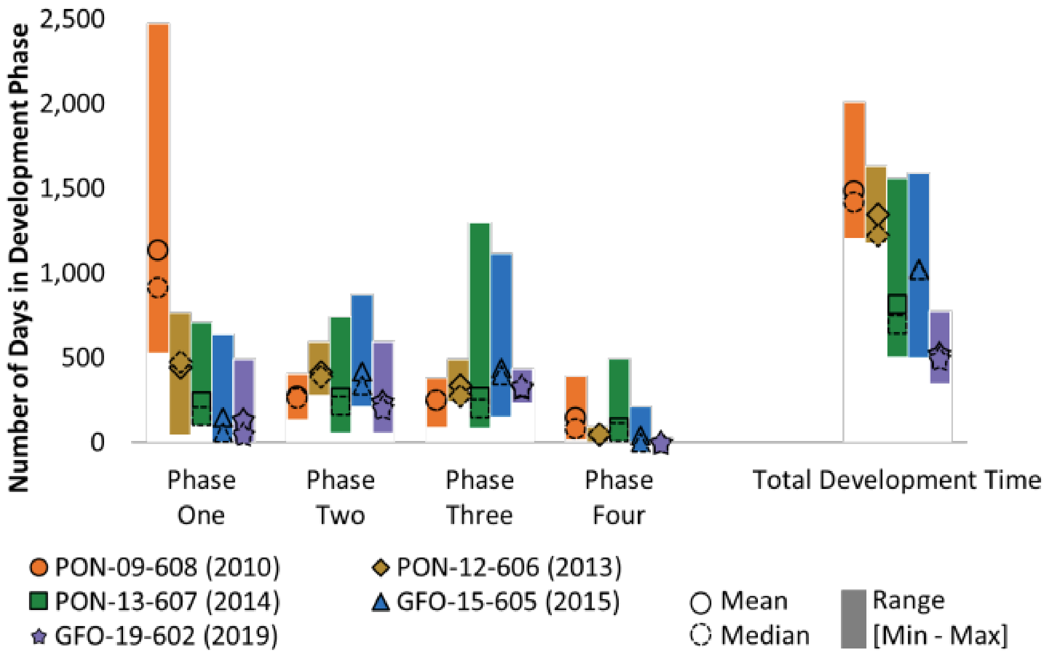
Hydrogen Development Schedule and Process – Review

A typical process of hydrogen refueling station development, assuming there are no administrative holdups and other major hiccups, takes approximately two years.



Overall, the time spent in Phase One continues to decrease significantly after 2010 for newer solicitations. The mean, median, and maximum of station development time for newer stations continue to increase as more stations completed. The median station development time for GFO-19-602 is significantly lower than the other solicitations, but only eight stations have completed all phases, and the rest of the stations are in development and still affected by the COVID pandemic effects.

Sources: CEC and CARB

Pre-application
- Engage with a city or county's planning agency
- Establish channels of communication and a permitting pathway

Planning Review
- Ensure a proposed station fits within a community's zoning codes
- Acquire planning approval

Building Review
- Ensure compliance with applicable structural, mechanical, and electrical codes and local ordinances

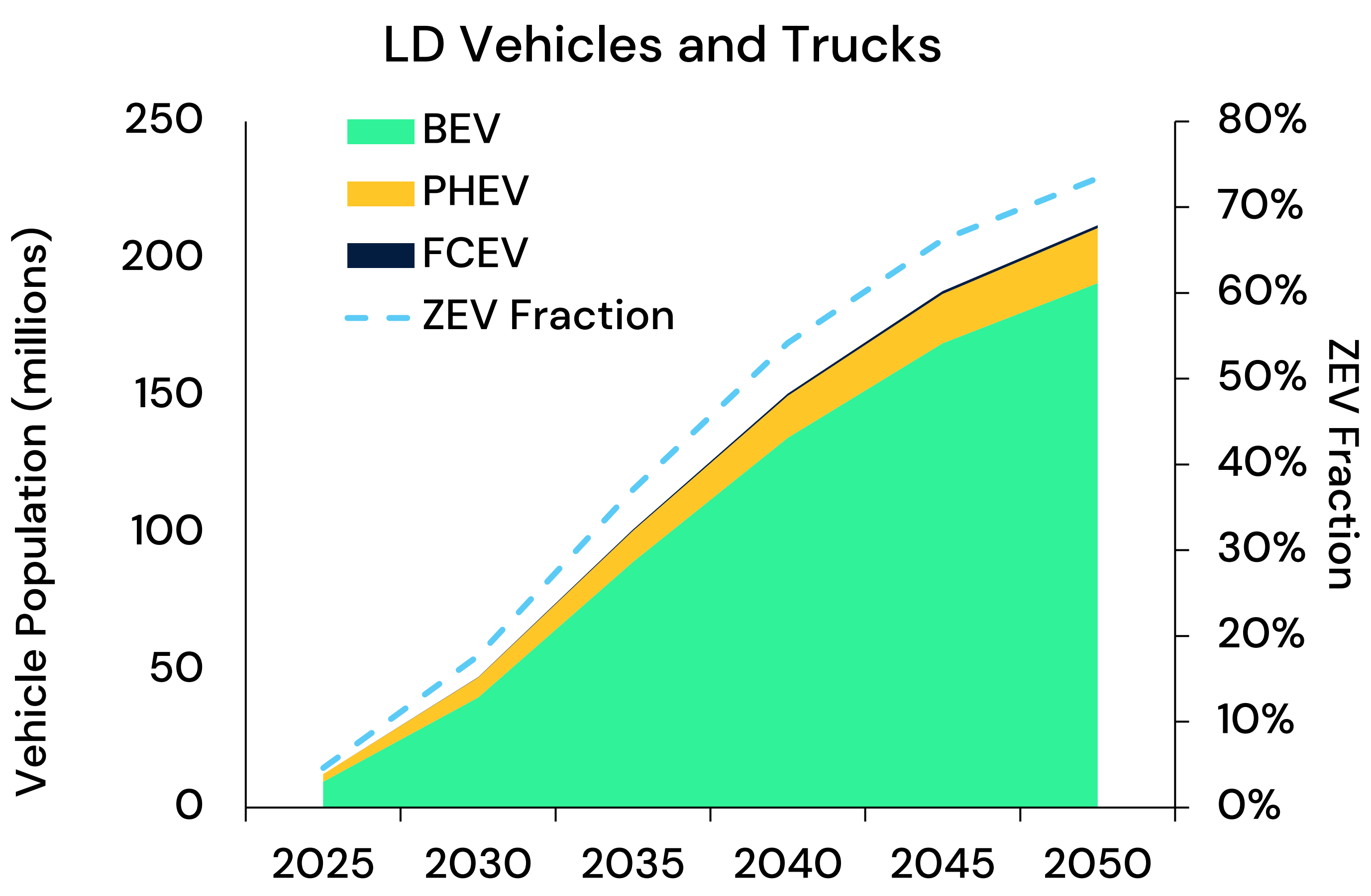
Construction
- Station construction work

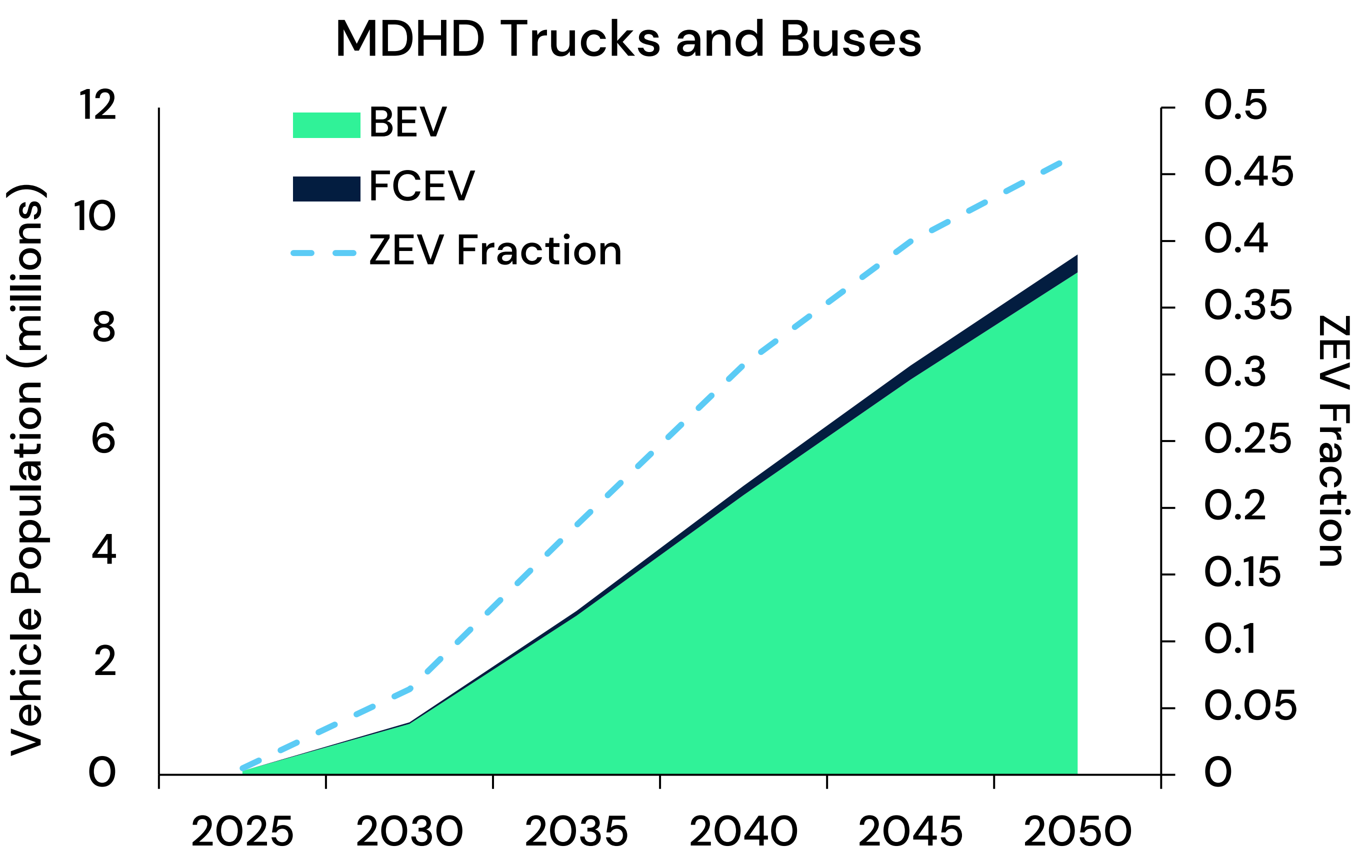
Commissioning
- Performance inspection
- Operational to open retail

Reference 1: Hydrogen Station Permitting Guidebook (ca.gov)
Reference 2: https://www.energy.ca.gov/sites/default/files/2021-05/CEC-600-2019-039.pdf
Reference 3: https://www.energy.ca.gov/sites/default/files/2022-12/CEC-600-2022-064.pdf

Infrastructure Needs and Demands Results

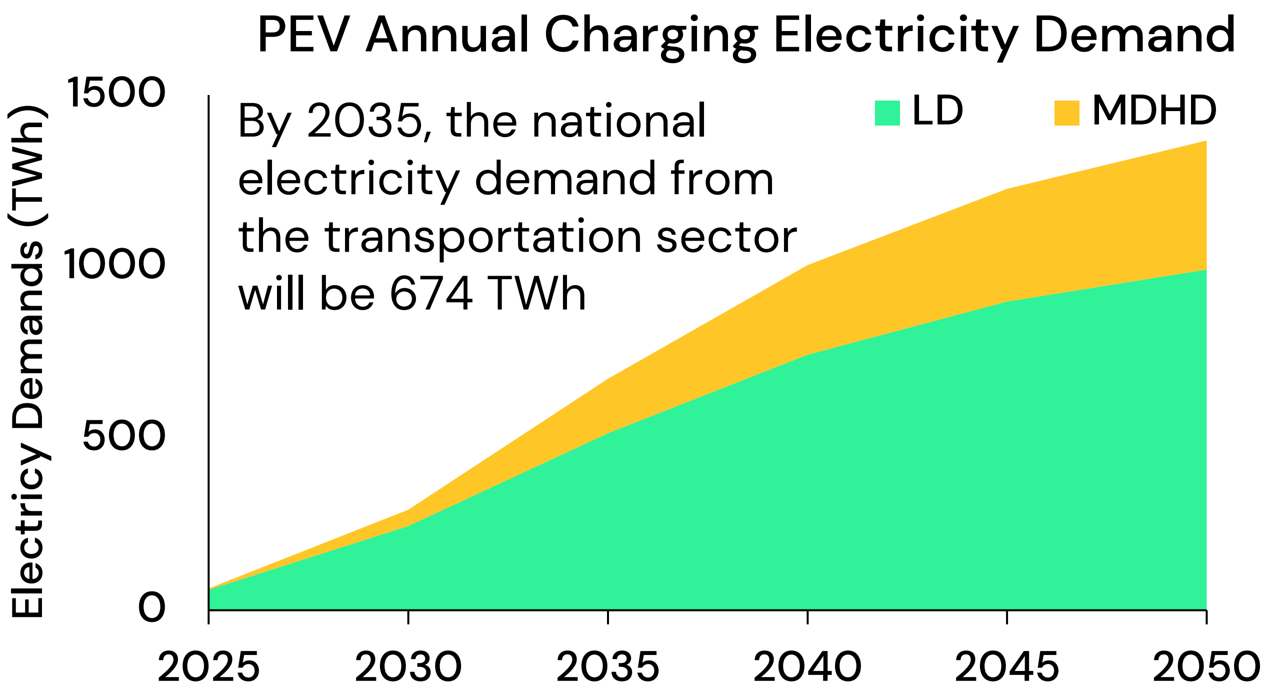
Fleet Composition for LD, MD and HD Vehicles

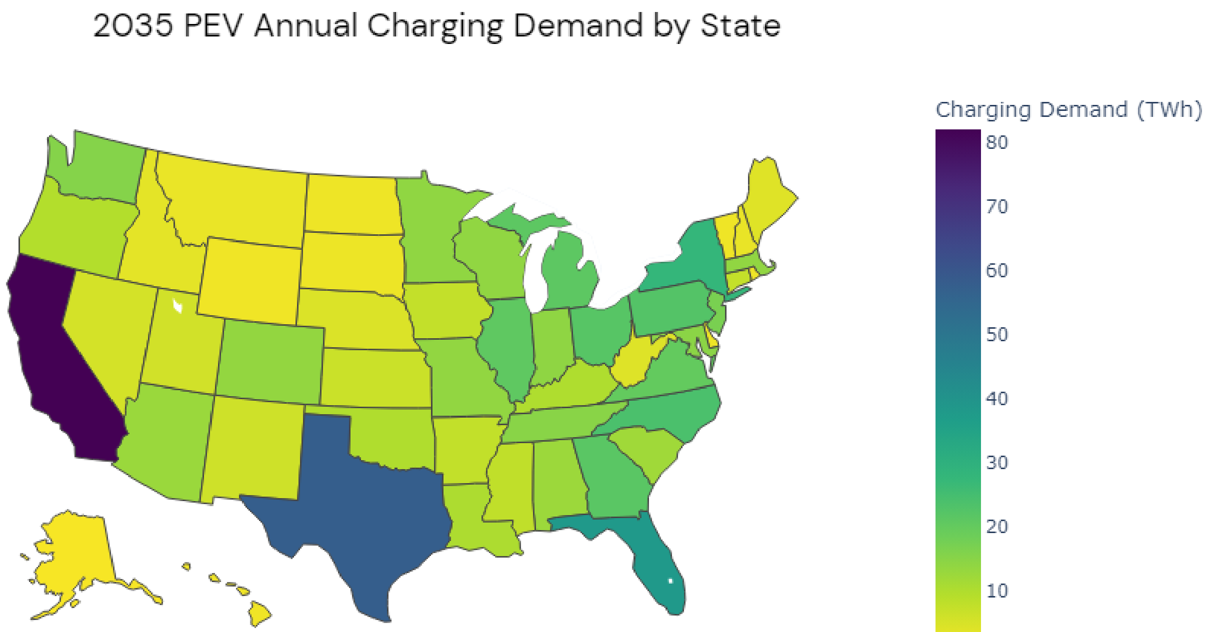


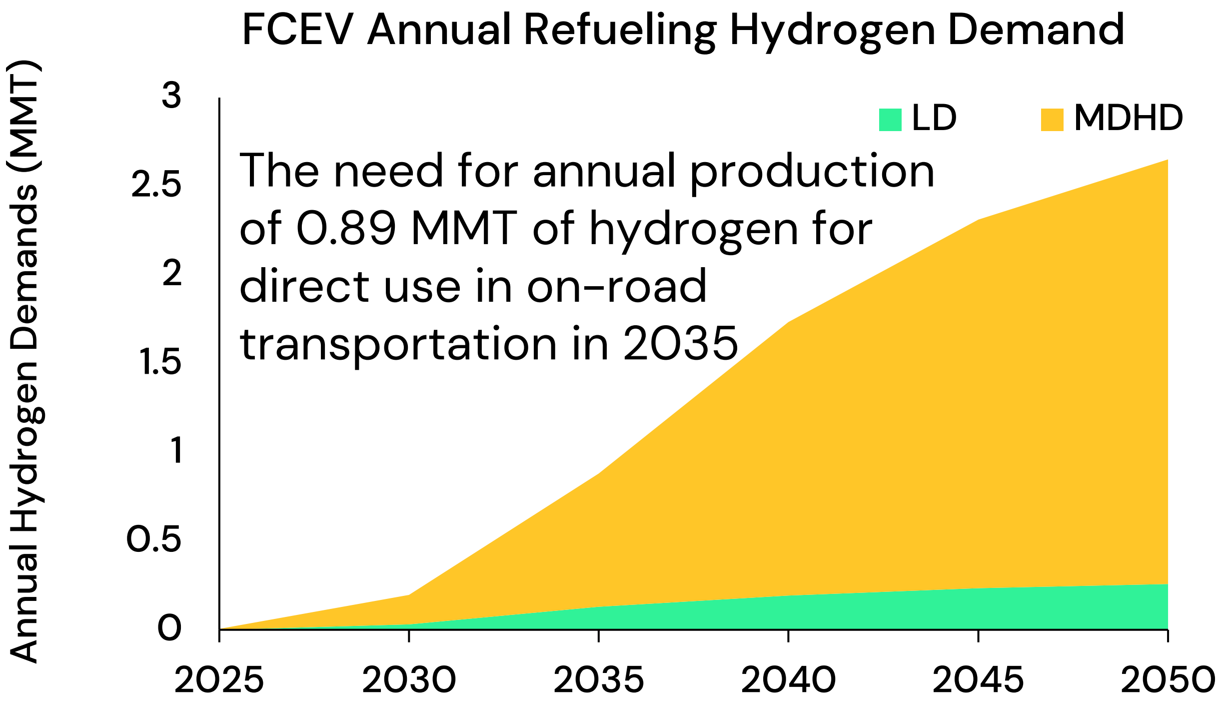


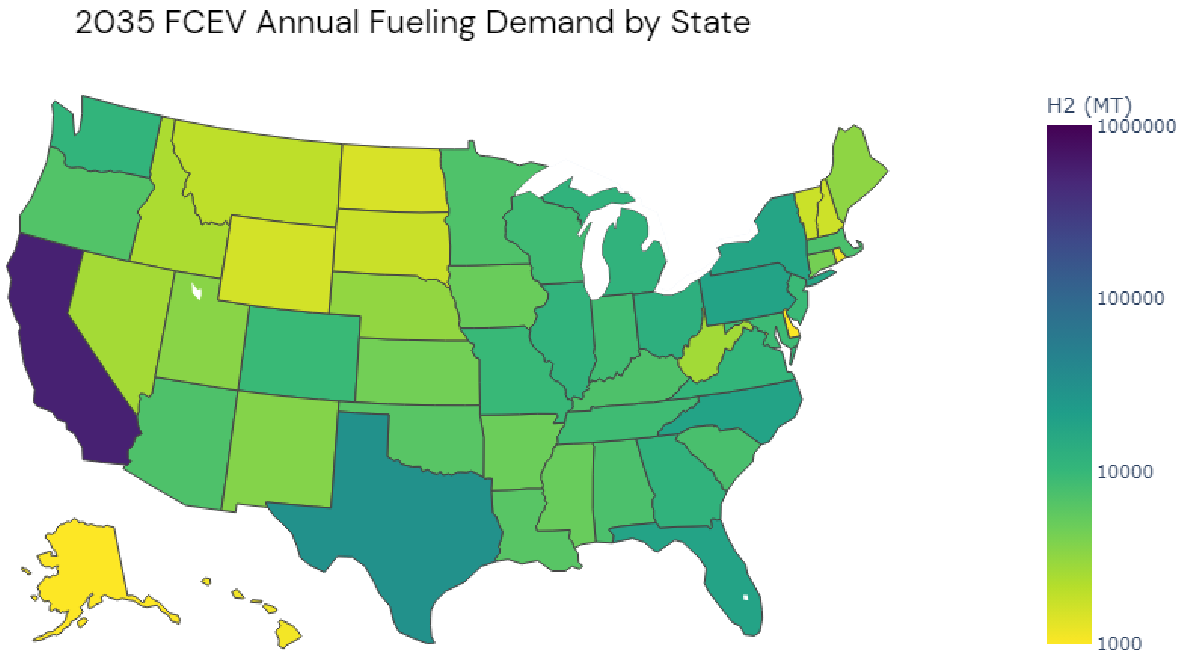
- The sales and technology penetration scenarios will achieve a national average of 37% ZEV fleets in the LD sector and 19% ZEV fleets in the MDHD sector by 2035, and 73% for LD and 46% for MDHD by 2050, respectively.
- It is also noteworthy that although the overall FCEV penetration may seem low, FCEV plays a significant role in the HD long-haul sector, accounting for 1% of the total fleet by 2035, and 6% by 2050.

Projected Energy Demand for Charging and Refueling



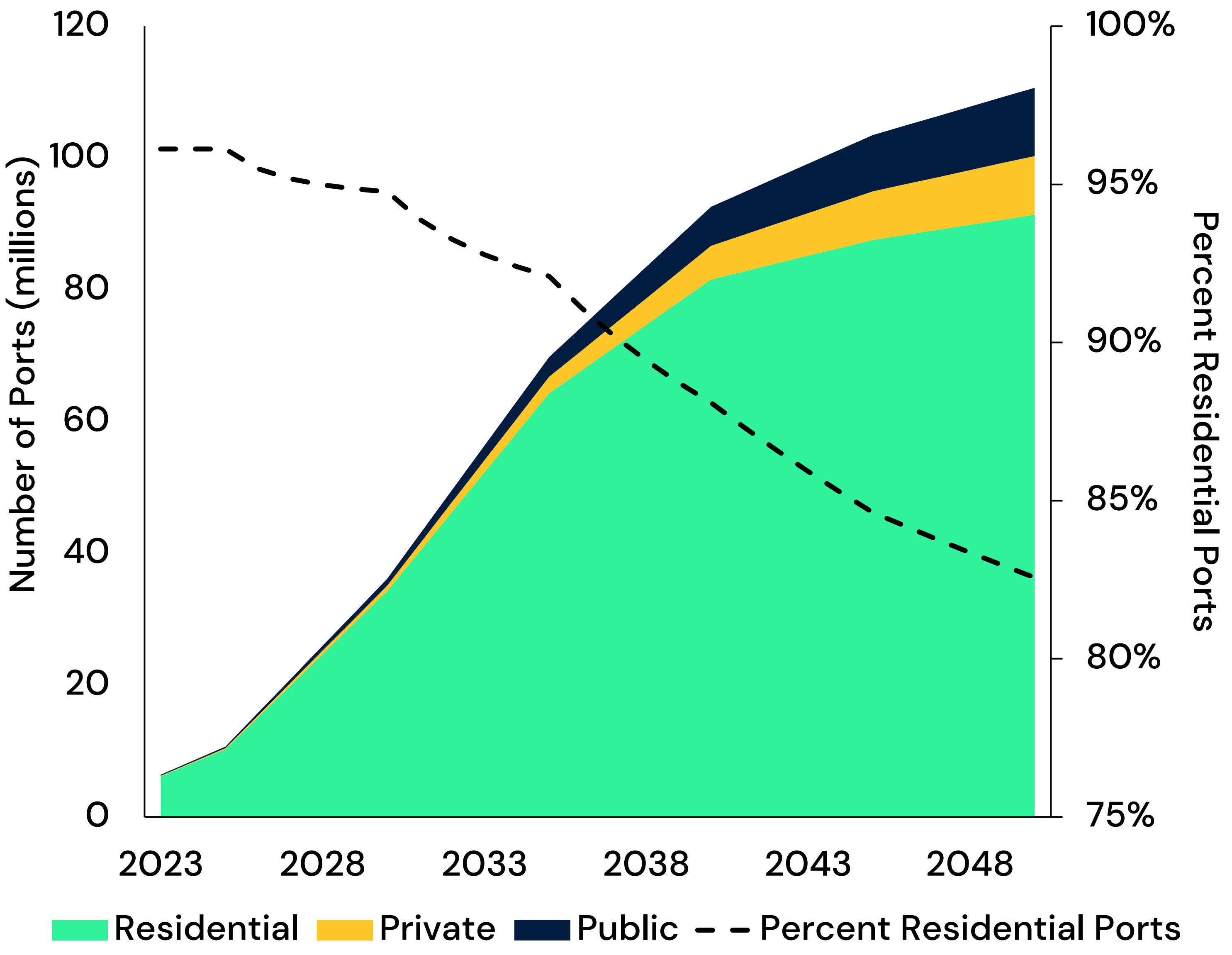




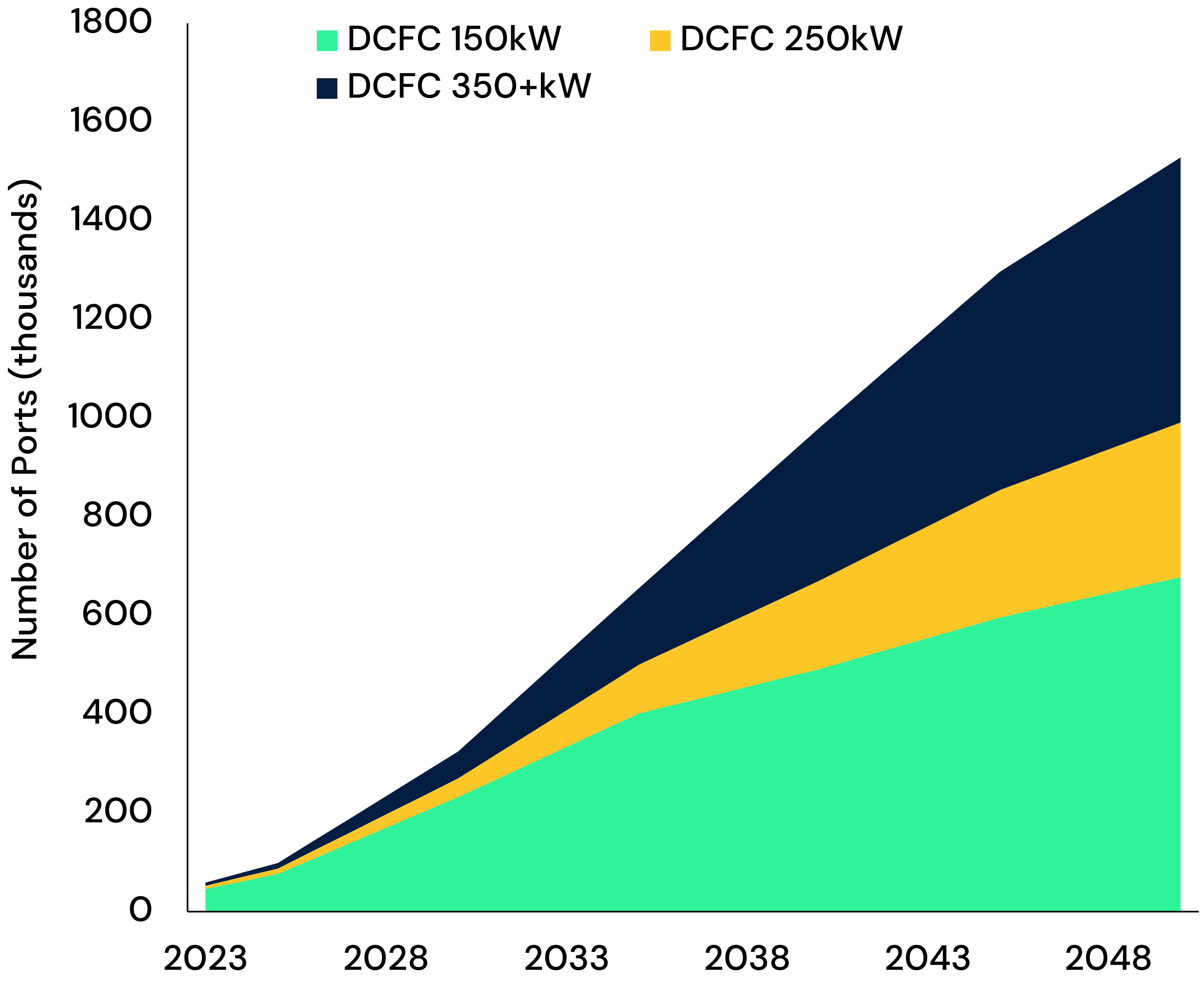


Passenger LD PEV Infrastructure: L1 and L2 Chargers

- Residential ports (e.g., private-access ports for residents of SFHs) are projected to fulfill majority of charging needs
  - Will consist of mainly L2 chargers and some L1 chargers
- Public ports (e.g., retail, recreation, occupational facilities) will provide significant L2 charging support
- Shared private ports (e.g., residents of MUDs and office spaces) will provide similar levels of L2 charging support and some L1 charging support

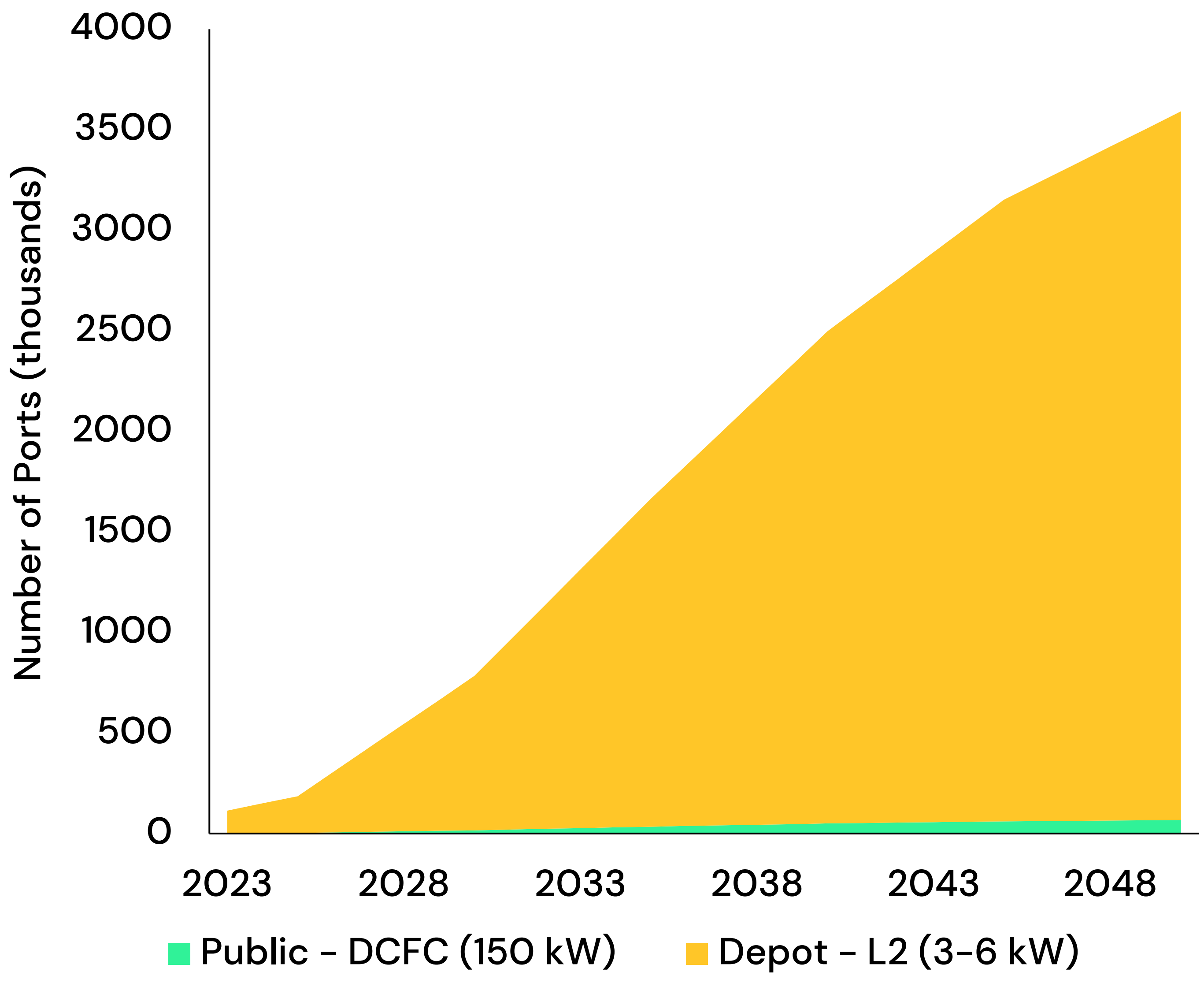


Passenger LD PEV Infrastructure: DCFCs



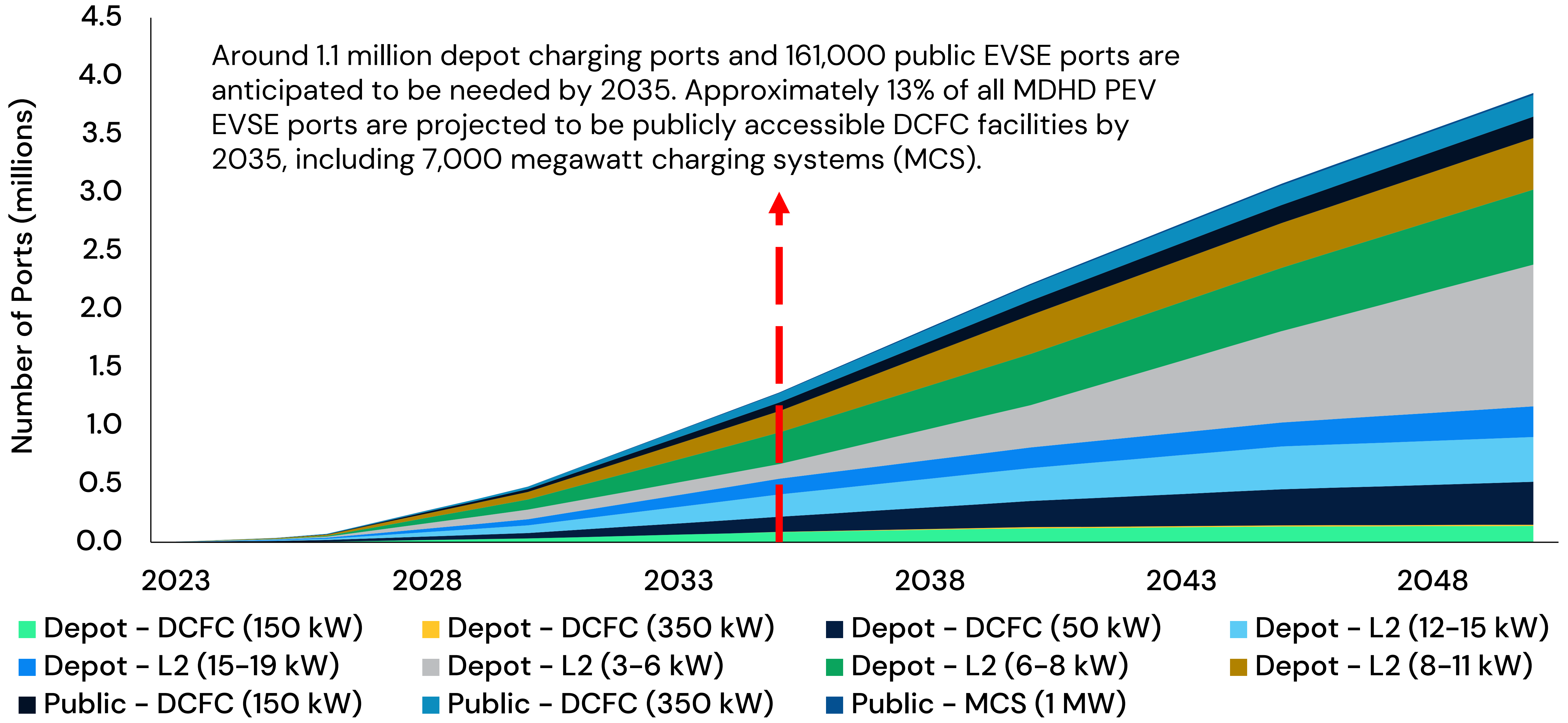
- Public DCFCs (e.g., retail and recreational centers) projected to offer charging speeds between 150 kW – 350+kW
- Higher capacity ports to incrementally phase in over time, likely following infrastructure readiness measures
- Accounted for PEVs in the TNC market, as well as long-distance road trips and their impact on charging demand

Light Commercial Truck Infrastructure



- Used ICF's proprietary models instead of NREL EVI-X suite due to its distinct travel patterns and charging needs;
- A significant share of light commercial trucks charging needs can be met by depot-access L2 ports;
- A portion of the depot charging needs of light commercial trucks can potentially be met using residential charging as well, especially for individual owner-operators, which is not considered in this study.

MDHD PEV Infrastructure – Total EVSE Ports



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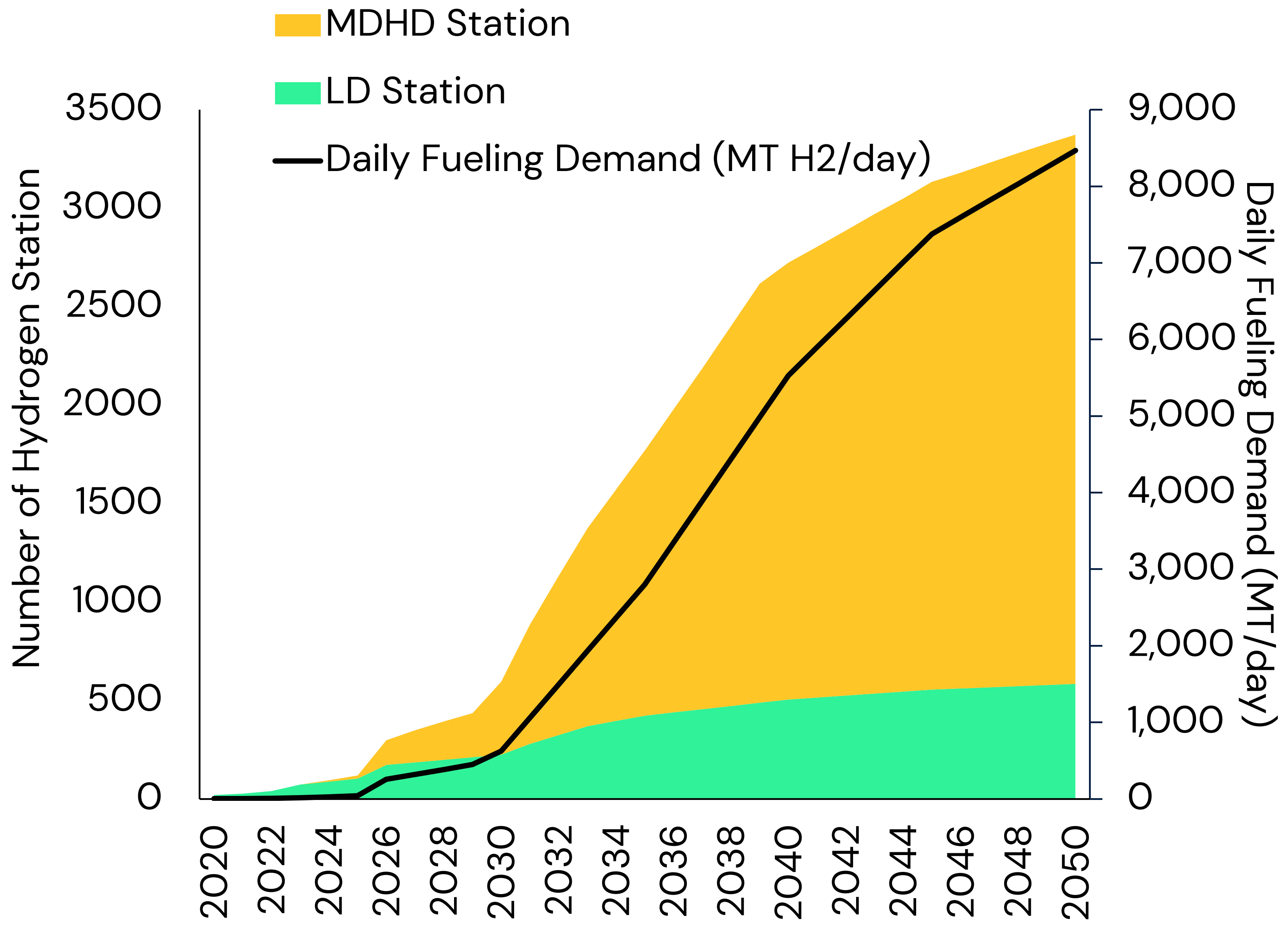
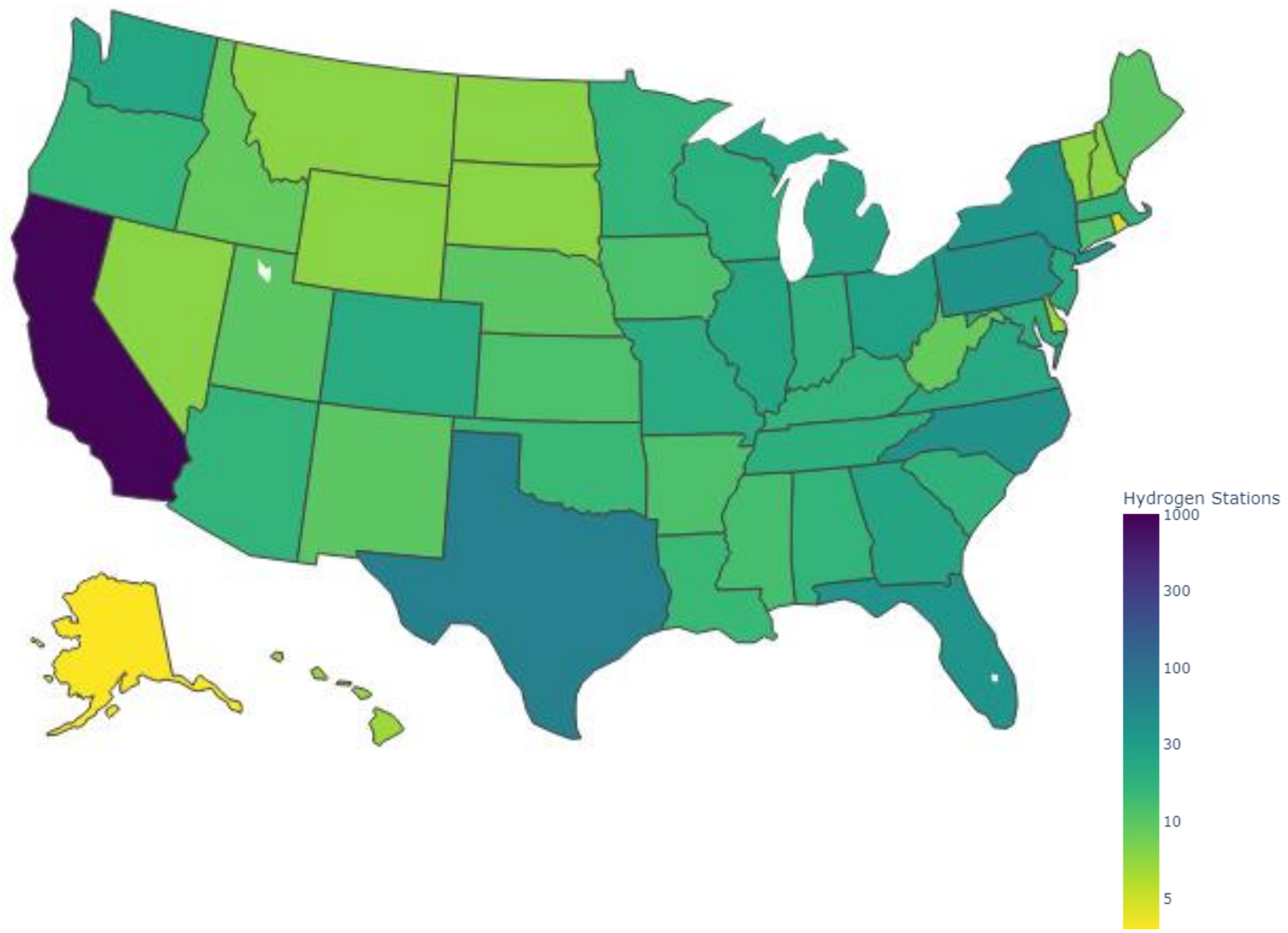
Hydrogen Refueling Stations and Fueling Demand

Total estimated hydrogen refueling stations and demand (MT/day).



Estimated hydrogen refueling stations by state in 2035



By 2035, the number of stations will increase to almost 1,800 to meet the hydrogen demand of over 2,800 MT per day, with 1,350 stations serving MDHD, and over 400 stations dedicated to LD.

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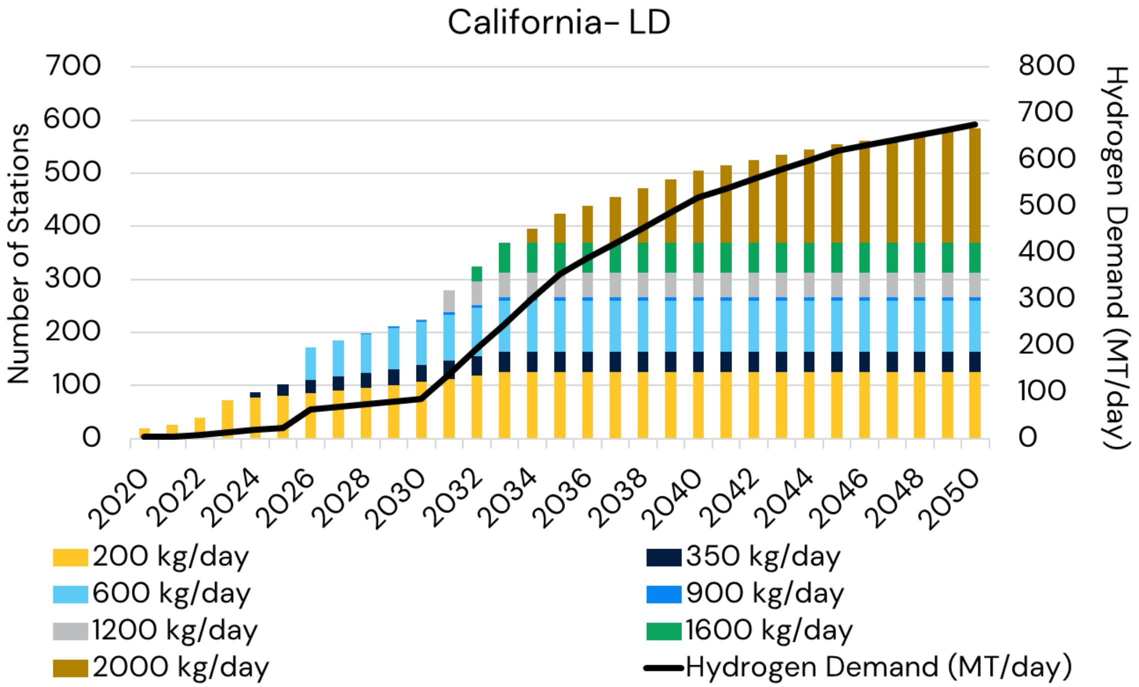
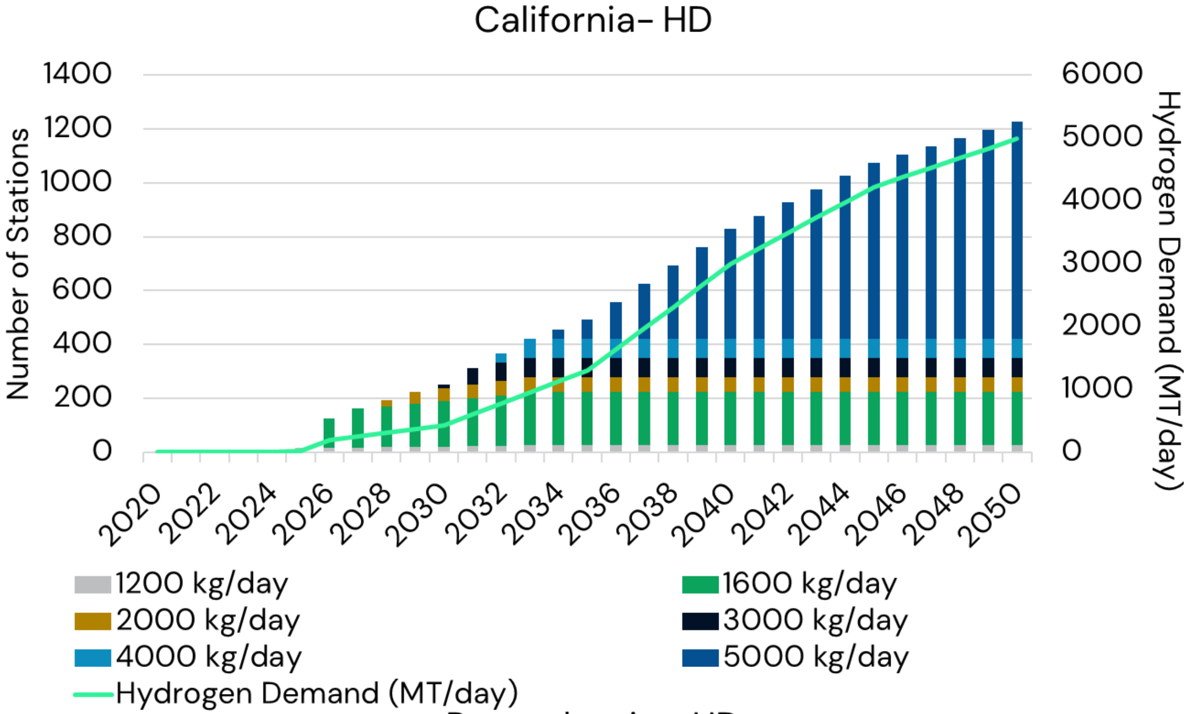
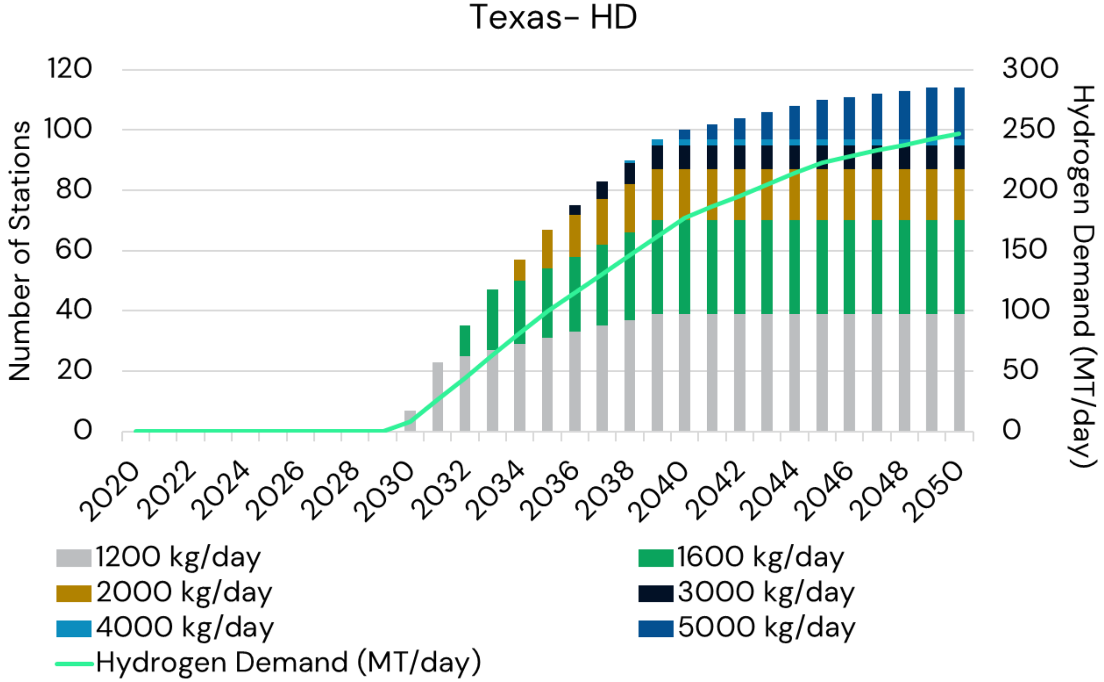
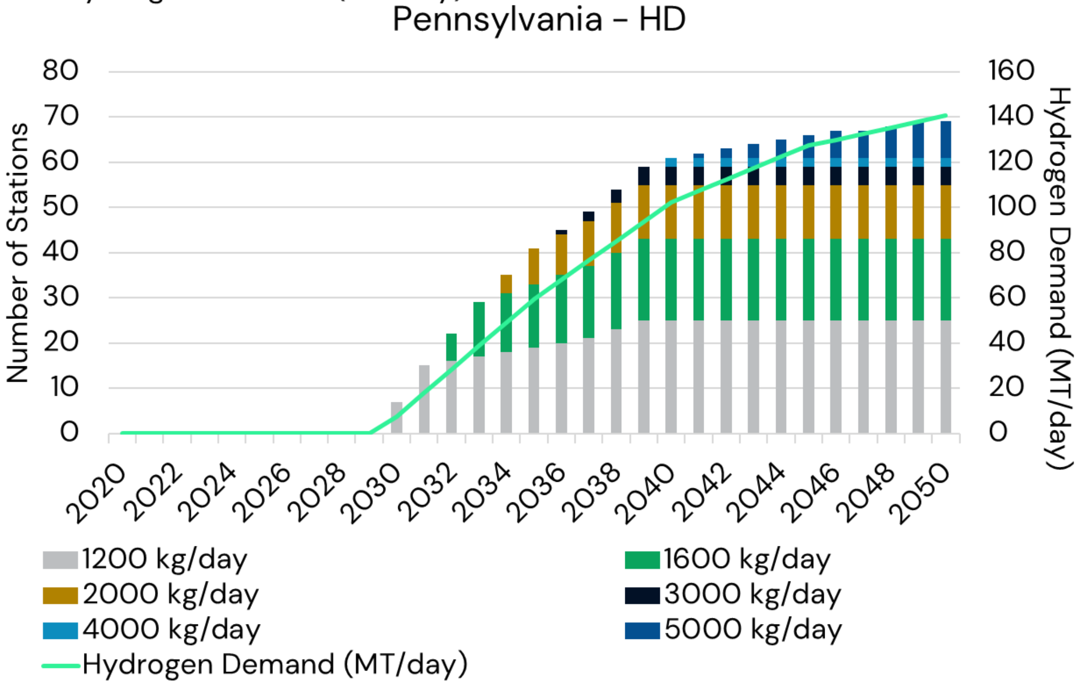
Hydrogen Capacity and Demand in Selected States

The largest demand for hydrogen is expected in California, driven by the ACC II, ACT, ICT, and ACF regulations, followed by Texas and Pennsylvania



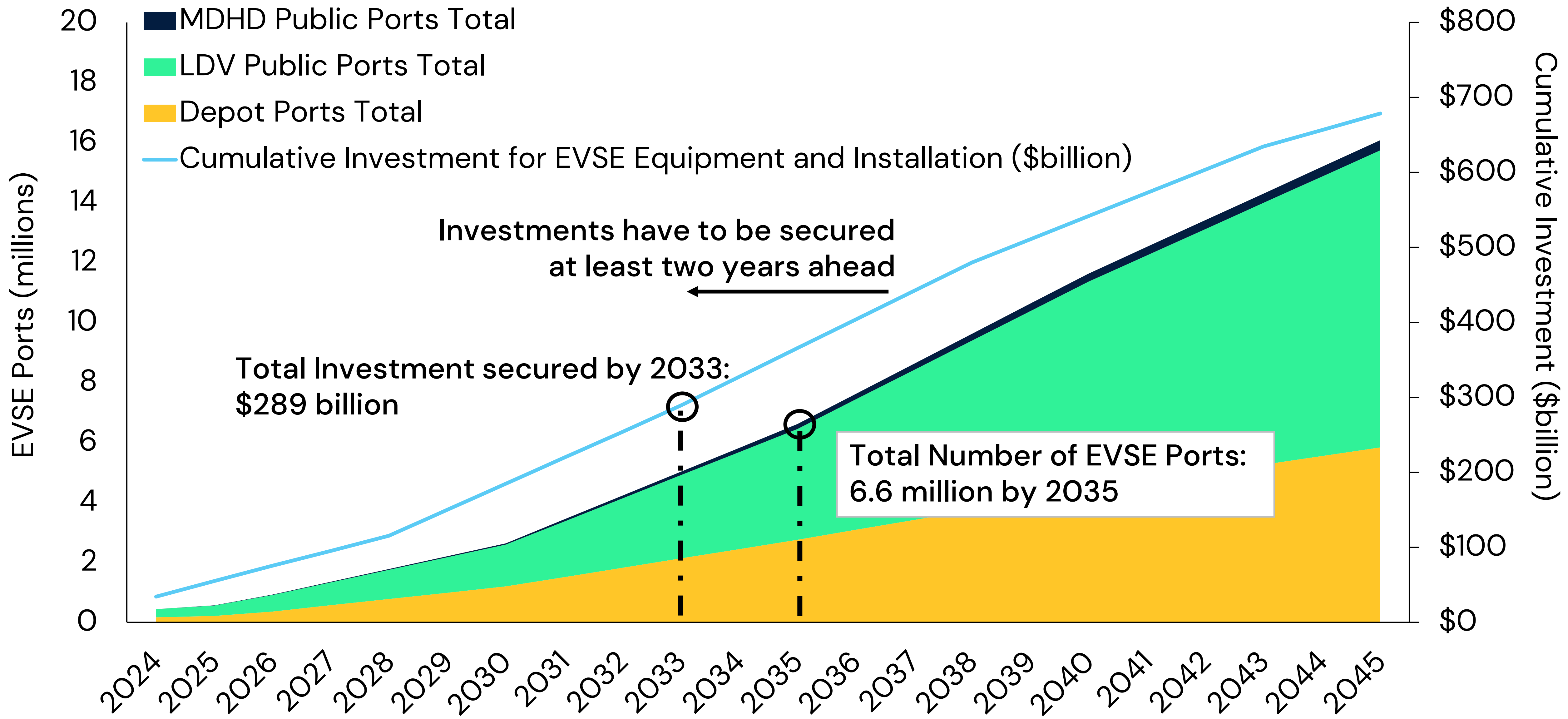






Charging Infrastructure Cost and Schedule Results

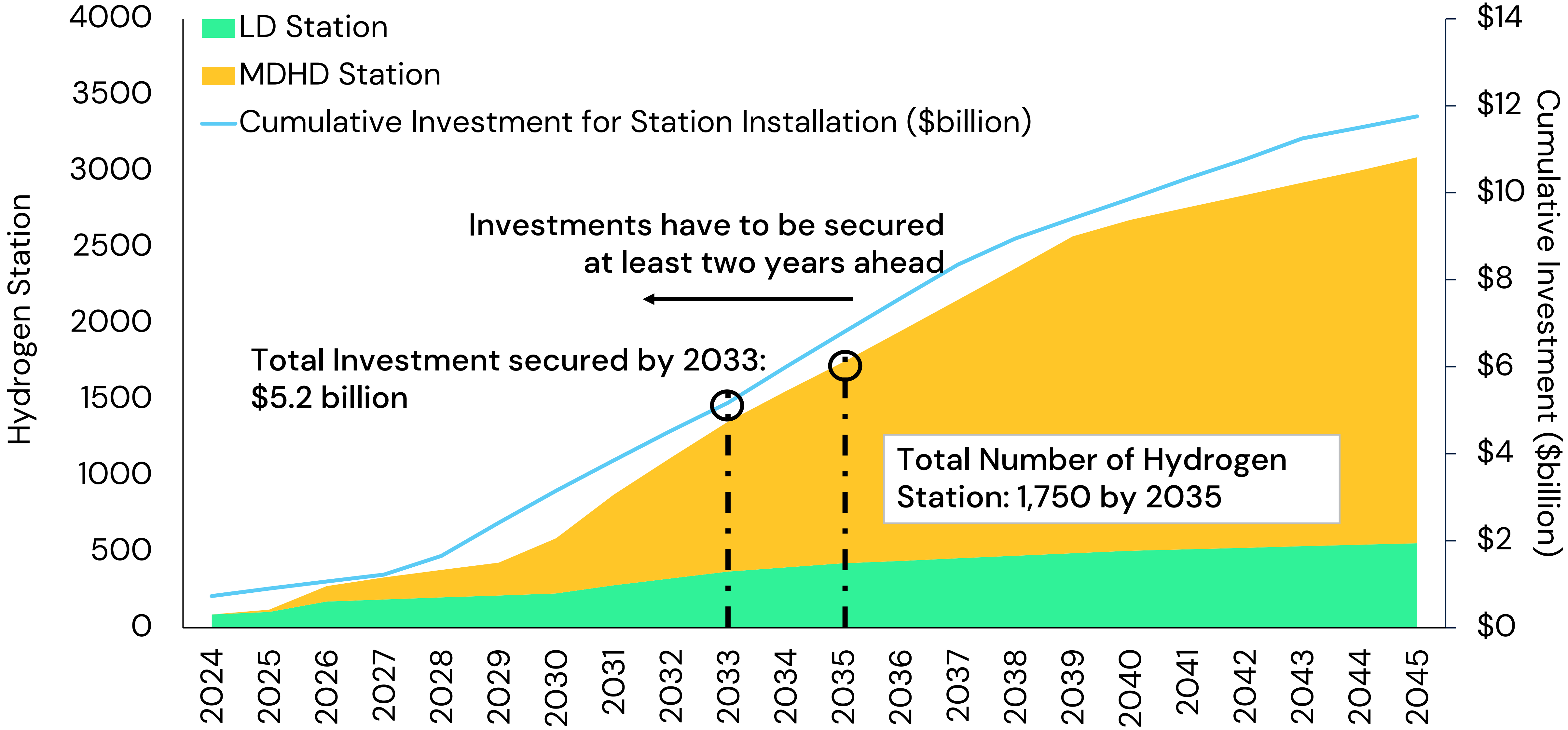
Total public and depot EVSE ports and cumulative investment needed for equipment and installation



The cost schedule incorporated consideration that investment has to be committed at least two years ahead to account for site development lead time before deployment.

Hydrogen Infrastructure Cost and Schedule Results

Total hydrogen fueling stations and needed investment for station installation

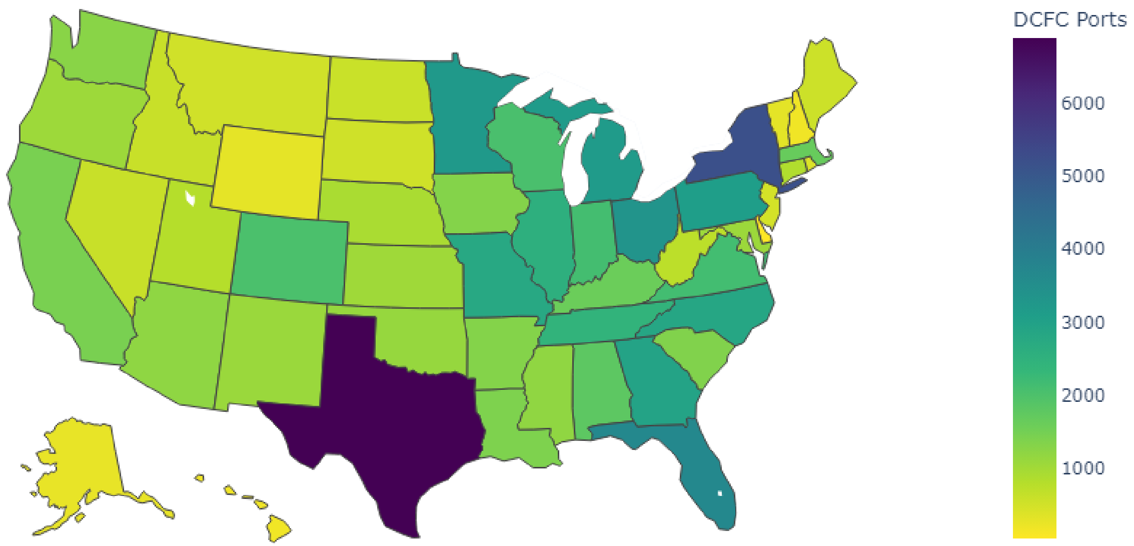


The cost schedule incorporated consideration that investment has to be committed at least two years ahead to account for site development lead time before deployment.

Discussion and Other Considerations

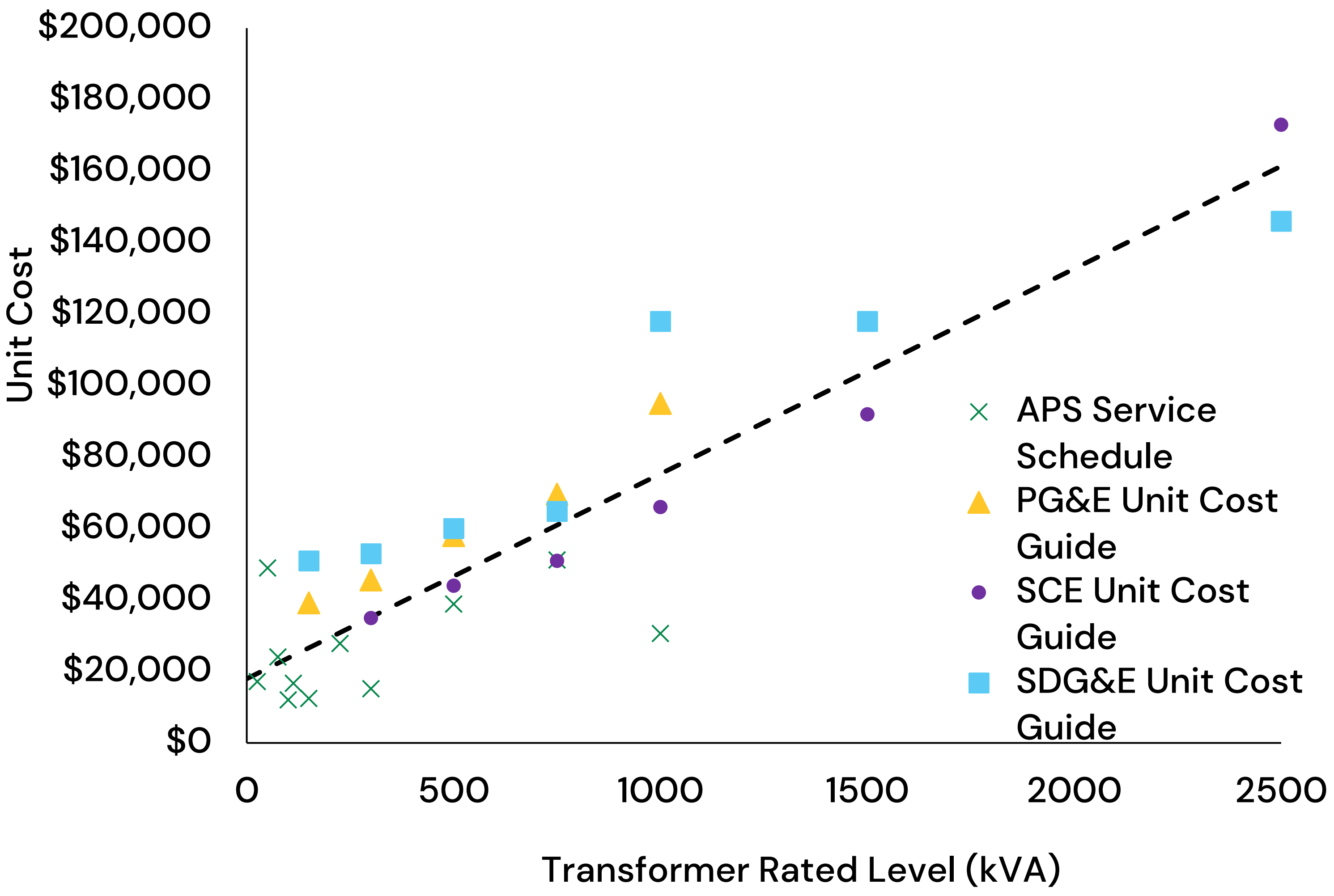
Other Key Considerations for PEV Charging

- Home charging access gaps
- Public charging infrastructure gaps
- Varying cost and timeline for grid upgrades and infrastructure make-ready



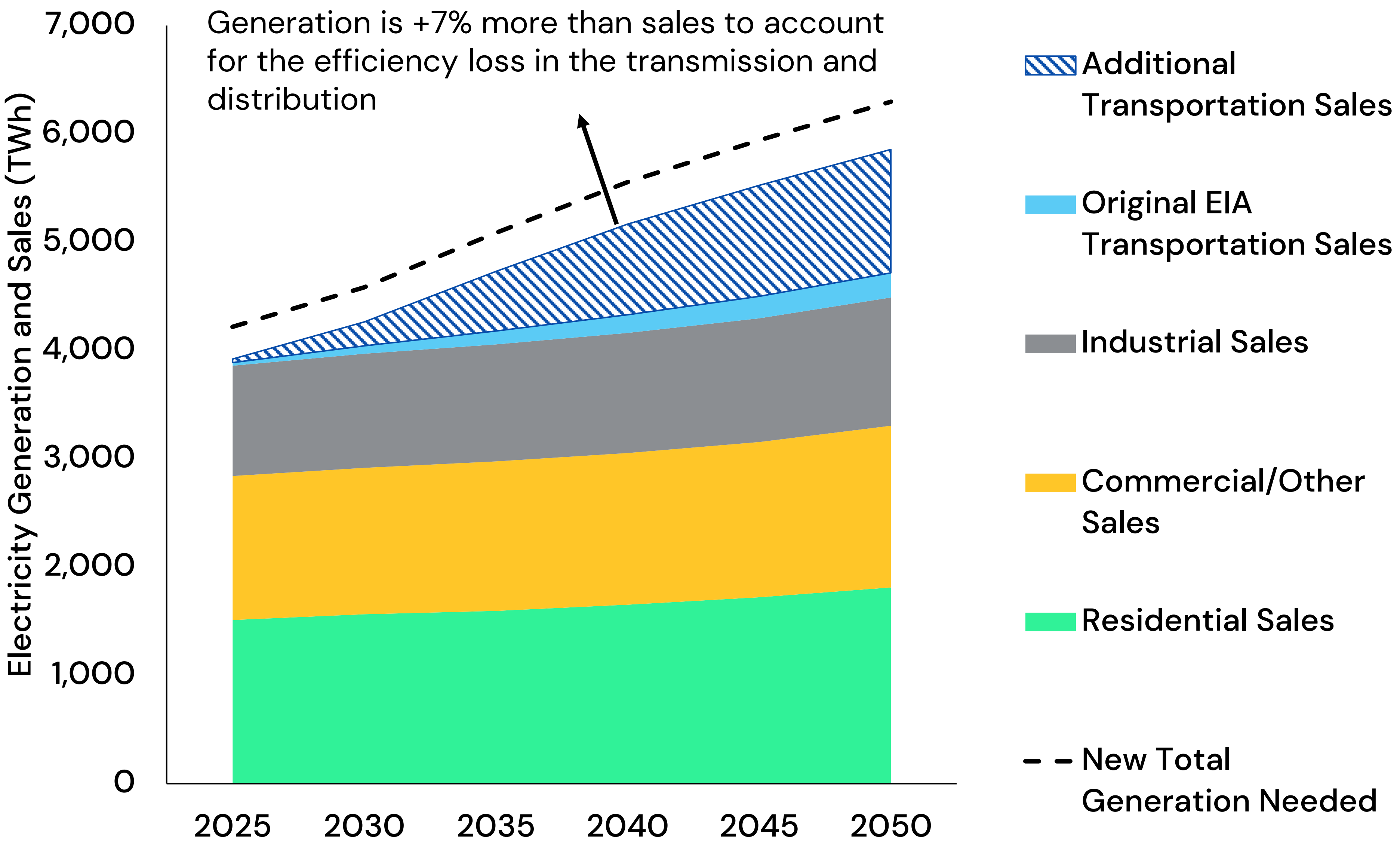
Number of new LDV DCFC charging ports needed by 2025

Transformer unit cost as a function of rated kVA

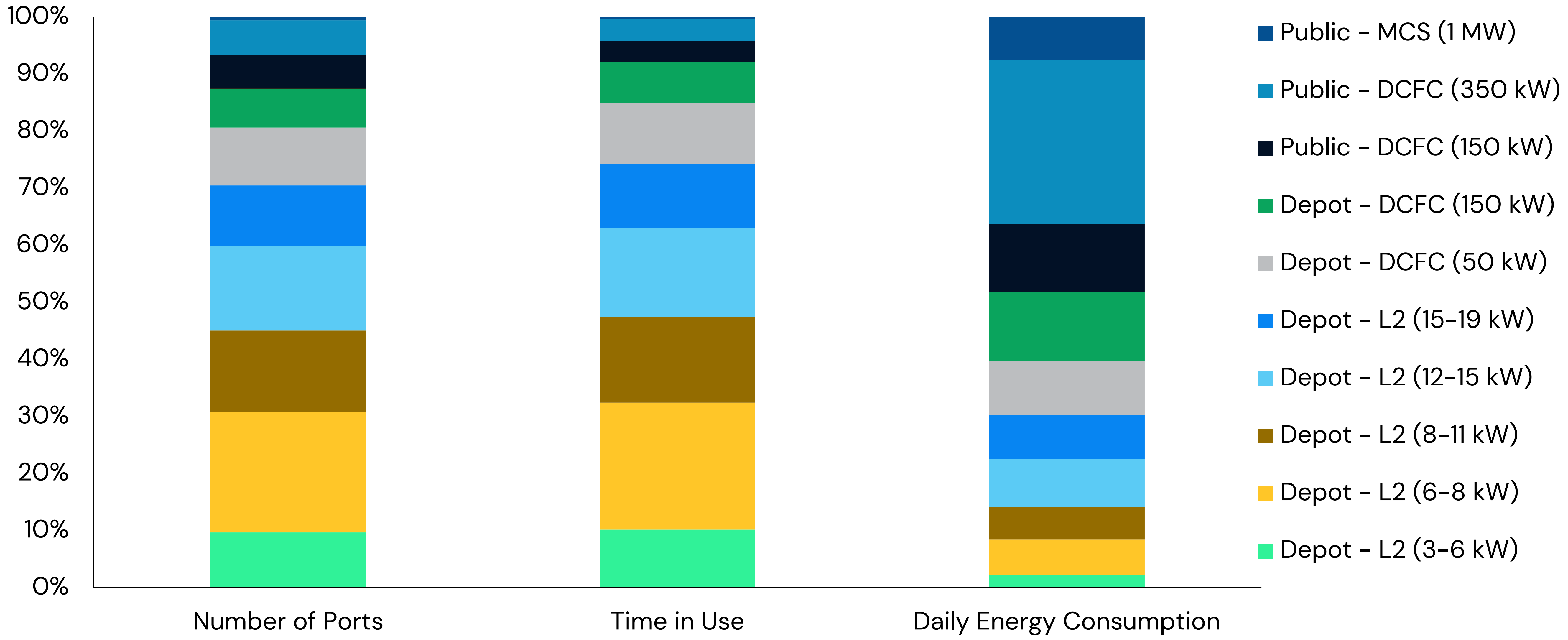


Impact on Overall Electricity Sales and Generation

- An additional 687 TWh generation will be needed from the power sector by 2035 and 1,319 TWh by 2050 compared to current EIA projection.
- The actual incremental need for generation will be impacted by many other factors, including electrification activities in other sectors, such as residential and commercial buildings.
- Factors such as distributed generation or additional managed charging could reduce the need for additional centralized generating resources.



Potential Impact of PEV Charging Events on Peak Load

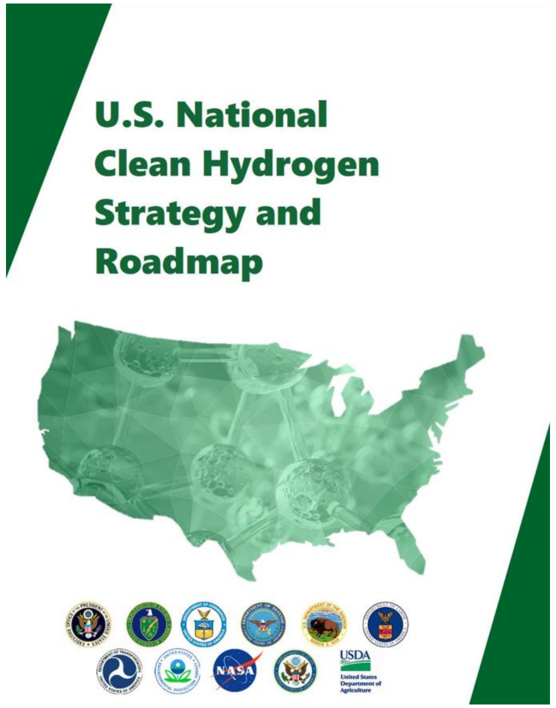


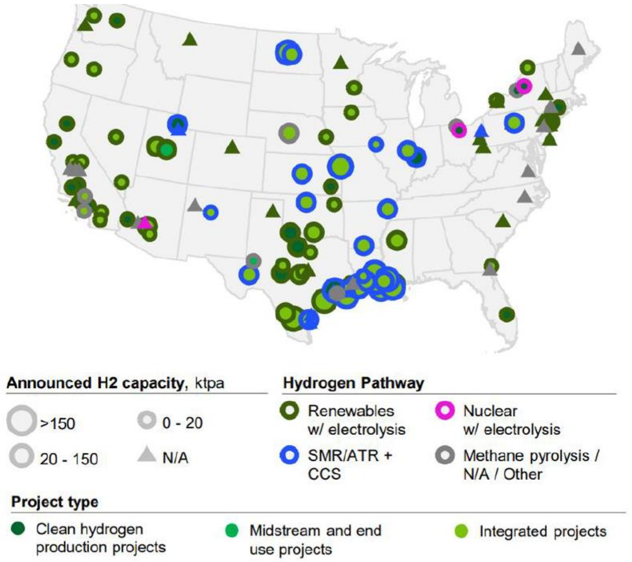
Despite the number of ports and total usage time for public MDHD chargers being minimal compared to depot chargers, they represent over 48% of the total daily charging demands for MDHD and light commercial trucks. If MDHD en-route charging consistently occurs during peak demand hours in the daytime, it could potentially impose a significant strain on the power grid.

Current Hydrogen Infrastructure Gaps – Refueling Stations & Hydrogen Production

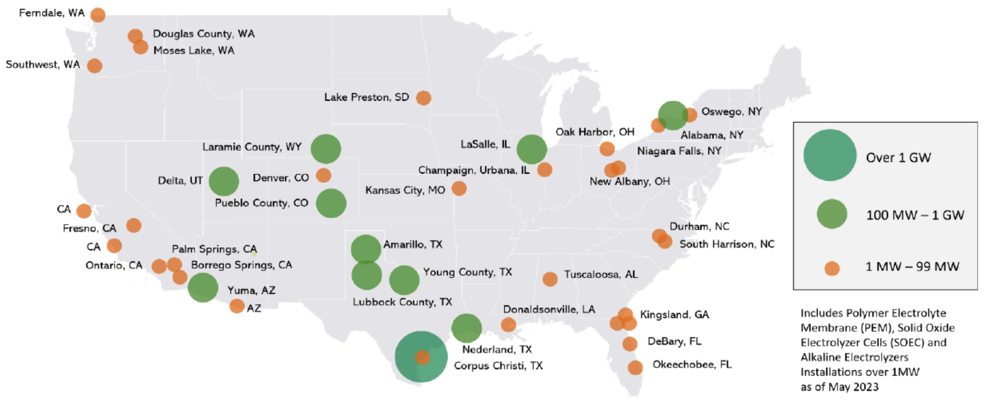
- The biggest gap of hydrogen infrastructure is the refueling station installation, simply because of the development of refueling stations is still in a relatively early stage with over 100 stations –open or planned – in California.

- Funding and incentives in hydrogen production will help to bridge the gap between the increasing demand for hydrogen as a transportation fuel and currently limited clean production.





(a) Currently publicly announced clean hydrogen production projects as of EOY 2022, with total production potential of 12 MMT/year. (Repurposed from DOE's report, Pathways to Commercial Liftoff: Clean Hydrogen[3])



(b) Planned and installed PEM electrolyzer capacity over 1 MW. Bubbles are for illustrative purposes only and not drawn to scale.[49]

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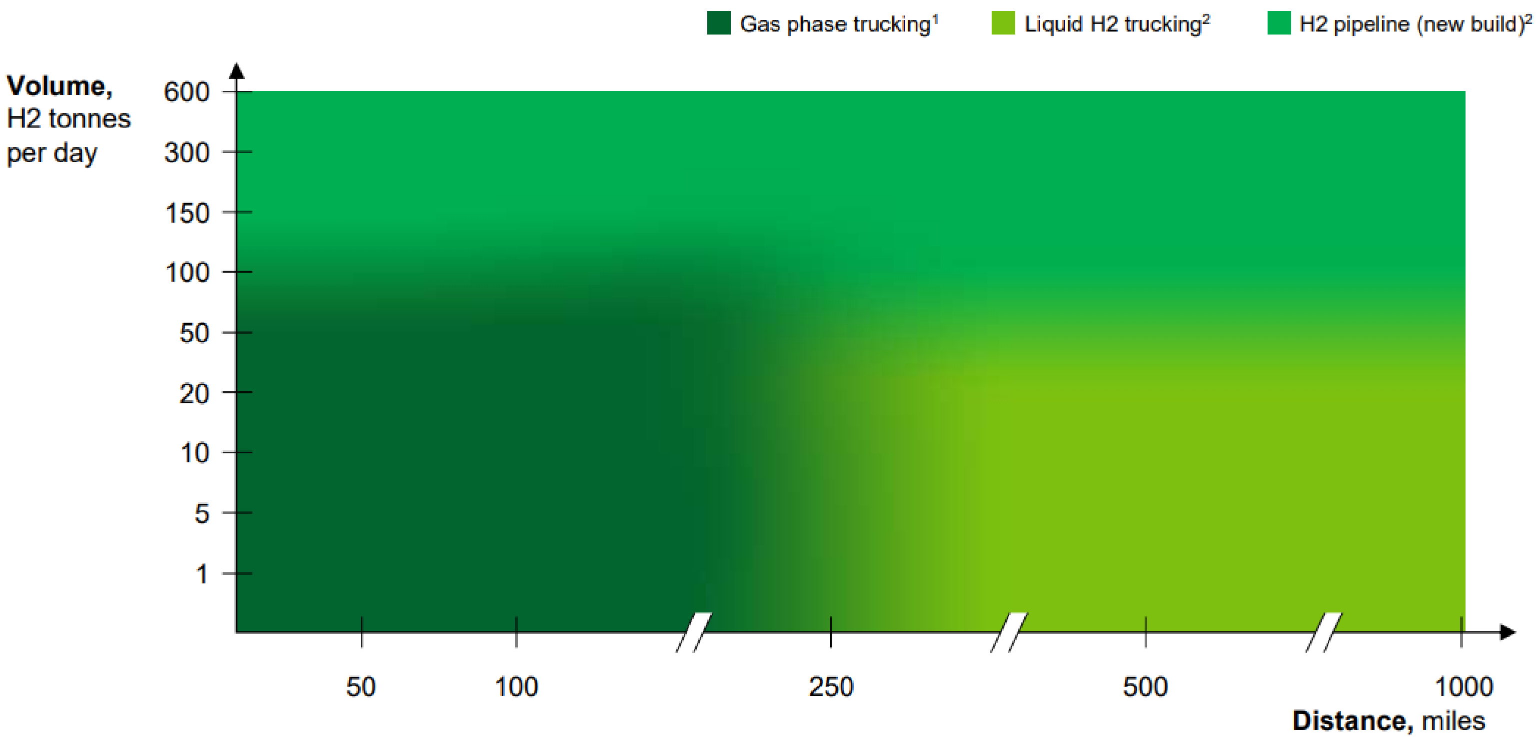
Reference 1: https://afdc.energy.gov/stations#/find/nearest?fuel=HY&hy_nonretail=true
Reference 2: https://www.hydrogen.energy.gov/pdfs/us-national-clean-hydrogen-strategy-roadmap.pdf

Other Hydrogen Infrastructure Considerations – Delivery and Distribution

Hydrogen distribution infrastructure will be essential to unlock use cases for hydrogen where production/offtake are not co-located. Pipelines could be critical anchors to this system, as they provide low-cost distribution and storage at scale. With the expected cost reduction in clean hydrogen production, the delivery and distribution cost could represent more than half of the delivered cost of hydrogen.

Preferred hydrogen distribution method by volume and distance



1 Assumes hydrogen is compressed to 500 bar and transported in 1100 kg truck
2 Includes liquefaction and liquid transport (fuel and labor)
3 Assumes hydrogen is compressed to 80 bar and transported in a newly built, dedicated H2 pipeline. These results do not consider leveraging existing pipelines

Source: Heatmap is based on data from the Hydrogen Council and the Hydrogen Delivery Scenario Analysis Model at Argonne National Laboratory, but left qualitative to highlight uncertainty in distribution methods and case-by-case variability

Distribution method	Key characteristics	2030 levelized cost, including compression / liquefaction, $/kg
Gas phase trucking[1]	• H2 **gas is compressed at ambient temperature** to 300 – 500 bar • **Ideal for short distances and small volumes** (≤ 20 TPD) due to lower capex costs for compressors and tube trailers vs. liquid and pipeline transport • **Lower transport capacity** due to the low volumetric density of H2	0.9-1.9
Liquid hydrogen trucking[2]	• **Cryogenic cooling to liquefy hydrogen**, followed by storage in cryogenic tankers • **Ideal for larger volumes where pipelines are not feasible** and longer distances to minimize the number of trips and driver labor cost • **Higher capex costs than gas phase trucking** but lower than pipelines	2.7-3.2
Dedicated hydrogen pipeline transport[3]	• **Underground pipeline** transporting compressed gas phase hydrogen • **Lowest levelized cost at high volumes** (50+ TPD) **and long distances** due to low opex costs; not commonly used for lower volumes • **Requires permitting approval and high upfront capex costs** ($2-10 million per (inch-mile) for 6–14-inch diameter pipes)	0.2-0.5
Hydrogen / natural gas blended pipeline	• **Blending of up to ~20% hydrogen by volume into natural gas pipelines** for use in the power and heating sectors • **Blending rates are limited** due to leakage and required compressor modifications, but work is underway to refine volume threshold • **Separation** of hydrogen from natural gas **can be very expensive**	*Dependent on blending volume and retrofit costs*

1 Assumes hydrogen compressed to 500 bar and transported 250 km; 50 TPD compression capacity; Source: Hydrogen Council
2 Assumes hydrogen liquefied and transported 250 km; 50 TPD compression capacity; Source: Hydrogen Council. Range based on increased leak rate and liquefaction costs.
3 Assumes 600 TPD hydrogen compressed to 80 bar and transported 300 km; range represents difference between high-cost region (New England) and low-cost region (Great Plains); Source: Hydrogen Delivery Scenario Analysis Model, Argonne National Laboratory

Reference : https://liftoff.energy.gov/wp-content/uploads/2023/03/20230320-Liftoff-Clean-H2-vPUB.pdf

List of Acronyms

Acronym	Description
AB	Assembly Bill
ACCII	Advanced Clean Cars II
ACF	Advanced Clean Fleets
ACT	Advanced Clean Trucks
AEO	Annual Energy Outlook
AFDC	Alternative Fuel Data Center
BEV	Battery Electric Vehicle
CARB	California Air Resources Board
CEC	California Energy Commission
DCFC	Direct Current Fast Charger
DOE	Department of Energy
EIA	Energy Information Administration
EPA	Environmental Protection Agency

Acronym	Description
EVI-Pro	Electric Vehicle Infrastructure Projection Tool
EVSE	Electric Vehicle Supply Equipment
FCEV	Fuel Cell Electric Vehicle
HD	Heavy Duty
ICT	Innovative Clean Transit
ICCT	International Council on Clean Transportation
ICEV	Internal Combustion Engine Vehicle
L1	Level 1 [Charger]
L2	Level 2 [Charger]
LD	Light Duty
MCS	Megawatt Charging System
MD	Medium Duty
MDHD	Medium- and Heavy-Duty
MT/MMT	Metric Tons/Million Metric Tons
MOVES	Motor Vehicle Emission Simulator Tool
NREL	National Renewable Energy Laboratory

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