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
The Coordinating Research Council, Inc. (CRC) is a non-profit corporation supported by the petroleum and automotive equipment industries with participation from other industries, companies, and governmental bodies on research programs of mutual interest. CRC operates through the committees made up of technical experts from industry and government who voluntarily participate. The five main areas of research within CRC are: air pollution (atmospheric and engineering studies); aviation fuels, lubricants, and equipment performance; heavy-duty vehicle fuels, lubricants, and equipment performance (e.g., diesel trucks); light-duty vehicle fuels, lubricants, and equipment performance (e.g., passenger cars); and sustainable mobility (e.g., decarbonization). CRC’s function is to provide the mechanism for joint research conducted by industries that will help in determining the optimum combination of products. CRC’s work is limited to research that is mutually beneficial to the industries involved. The final results of the research conducted by, or under the auspices of, CRC are available to the public.

LEGAL NOTICE
This report was prepared by ICF as an account of work sponsored by the Coordinating Research Council (CRC). Neither the CRC, members of the CRC, ICF, nor any person acting on their behalf: (1) makes any warranty, express or implied, with respect to the use of any information, apparatus, method, or process disclosed in this report, or (2) assumes any liabilities with respect to use of, inability to use, or damages resulting from the use or inability to use, any information, apparatus, method, or process disclosed in this report. In formulating and approving reports, the appropriate committee of the Coordinating Research Council, Inc. has not investigated or considered patents which may apply to the subject matter. Prospective users of the report are responsible for protecting themselves against liability for infringement of patents.
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

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

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

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

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

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

<table>
<thead>
<tr>
<th>Combination Long-haul Truck</th>
<th>312</th>
<th>9.77</th>
<th>0.1</th>
<th>1:1</th>
<th>0.675</th>
<th>350</th>
<th>0.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combination Short-haul Truck</td>
<td>312</td>
<td>6.5</td>
<td>0.59</td>
<td>1:1</td>
<td>0.41</td>
<td>1000</td>
<td>0.2</td>
</tr>
<tr>
<td>Light Commercial Truck</td>
<td>312</td>
<td>2.81</td>
<td>0.72</td>
<td>2:1</td>
<td>0.28</td>
<td>150</td>
<td>0.2</td>
</tr>
<tr>
<td>Other Buses</td>
<td>292</td>
<td>8.73</td>
<td>1</td>
<td>1:1</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Refuse Truck</td>
<td>312</td>
<td>5.68</td>
<td>1</td>
<td>2:1</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>School Bus</td>
<td>327</td>
<td>2.45</td>
<td>1</td>
<td>2:1</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>Single Unit Long-haul Truck</td>
<td>312</td>
<td>5.18</td>
<td>0.59</td>
<td>2:1</td>
<td>0.41</td>
<td>150</td>
<td>0.2</td>
</tr>
<tr>
<td>Single Unit Short-haul Truck</td>
<td>312</td>
<td>3.42</td>
<td>0.72</td>
<td>2:1</td>
<td>0.28</td>
<td>150</td>
<td>0.2</td>
</tr>
<tr>
<td>Transit Bus</td>
<td>327</td>
<td>9.06</td>
<td>1</td>
<td>1:1</td>
<td>0</td>
<td>N/A</td>
<td>N/A</td>
</tr>
</tbody>
</table>

• 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.

<table>
<thead>
<tr>
<th>Max of kW Range</th>
<th>Charging Level</th>
<th>kW Range</th>
<th>Average Hardware Cost – Networked</th>
<th>Average Installation Cost – Networked</th>
<th>Total Hardware &amp; Installation Cost – Networked</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>L2</td>
<td>L2 (3-6 kW)</td>
<td>$2,500</td>
<td>$3,500</td>
<td>$6,000</td>
</tr>
<tr>
<td>8</td>
<td>L2</td>
<td>L2 (6-8 kW)</td>
<td>$3,000</td>
<td>$3,500</td>
<td>$6,500</td>
</tr>
<tr>
<td>11</td>
<td>L2</td>
<td>L2 (8-11 kW)</td>
<td>$3,500</td>
<td>$3,500</td>
<td>$7,000</td>
</tr>
<tr>
<td>15</td>
<td>L2</td>
<td>L2 (12-15 kW)</td>
<td>$4,000</td>
<td>$3,500</td>
<td>$7,500</td>
</tr>
<tr>
<td>19</td>
<td>L2</td>
<td>L2 (16-19 kW)</td>
<td>$4,500</td>
<td>$3,500</td>
<td>$8,000</td>
</tr>
<tr>
<td>50</td>
<td>DCFC</td>
<td>DCFC (50 kW)</td>
<td>$35,800</td>
<td>$28,100</td>
<td>$63,900</td>
</tr>
<tr>
<td>150</td>
<td>DCFC</td>
<td>DCFC (150 kW)</td>
<td>$100,000</td>
<td>$42,200</td>
<td>$142,200</td>
</tr>
<tr>
<td>350</td>
<td>DCFC</td>
<td>DCFC (350 kW)</td>
<td>$150,000</td>
<td>$61,600</td>
<td>$211,600</td>
</tr>
<tr>
<td>2000</td>
<td>MW</td>
<td>2 MW</td>
<td>$600,000</td>
<td>$130,000</td>
<td>$730,000</td>
</tr>
</tbody>
</table>

Sources:
ICF 2022: https://www.icf.com/insights/transportation/electric-vehicle-charging-infrastructure-costs
RMI 2014: https://rmi.org/pulling-back-veil-ev-charging-station-costs/
EPRI 2013: https://www.epri.com/research/products/0000000003002000577
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.

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

- Once a category of station capacity is phased-in, 5% 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.

Hydrogen Infrastructure Station Installation Cost – Assumptions

Cost Reduction (Moore’s Law)

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

Cost Model: $/($/kg/day) = $28,000*(Capacity/100)^{-0.95}

R^2 = 0.81

AB8 Maximum = $26,000/kg
AB8 Average = $13,000/kg
AB8 Minimum = $5,000/kg

Project | Daily Capacity | Refueling Station Specs | Liquid or Gaseous | Estimated Costs (Total funding)
--- | --- | --- | --- | ---
Shell81 | 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 Facility42 | 1,750 kg | Not Available | Not Available | $4.4M

Average cost per dispensed capacity (daily capacity) ~ $2600/kg

Reference 2: Feasibility study of EPA NPRM Phase 3 GHG standards for Medium Heavy-Duty Vehicles (Truck and Engine Manufacturers Associations)
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.
A typical process of hydrogen refueling station development, assuming there are no administrative holdups and other major hiccups, takes approximately two years.

**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)
Infrastructure Needs and Demands Results
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.
By 2035, the national electricity demand from the transportation sector will be 674 TWh.

The need for annual production of 0.89 MMT of hydrogen for direct use in on-road transportation in 2035.
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
• 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.
Around 1.1 million depot charging ports and 161,000 public EVSE ports are anticipated to be needed by 2035. Approximately 13% of all MDHD PEV EVSE ports are projected to be publicly accessible DCFC facilities by 2035, including 7,000 megawatt charging systems (MCS).
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.
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.
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.

Total Investment secured by 2033: $289 billion

Total Number of EVSE Ports: 6.6 million by 2035
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.

Total Investment secured by 2033: $5.2 billion

Total Number of Hydrogen Station: 1,750 by 2035
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
• 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.

Generation is +7% more than sales to account for the efficiency loss in the transmission and distribution.
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.

Reference 1: https://afdc.energy.gov/stations#/?fuel=HY&hy_nonretail=true
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.

# List of Acronyms

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AB</td>
<td>Assembly Bill</td>
<td>EVI-Pro</td>
<td>Electric Vehicle Infrastructure Projection Tool</td>
</tr>
<tr>
<td>ACCII</td>
<td>Advanced Clean Cars II</td>
<td>EVSE</td>
<td>Electric Vehicle Supply Equipment</td>
</tr>
<tr>
<td>ACF</td>
<td>Advanced Clean Fleets</td>
<td>FCEV</td>
<td>Fuel Cell Electric Vehicle</td>
</tr>
<tr>
<td>ACT</td>
<td>Advanced Clean Trucks</td>
<td>HD</td>
<td>Heavy Duty</td>
</tr>
<tr>
<td>AEO</td>
<td>Annual Energy Outlook</td>
<td>ICT</td>
<td>Innovative Clean Transit</td>
</tr>
<tr>
<td>AFDC</td>
<td>Alternative Fuel Data Center</td>
<td>ICCT</td>
<td>International Council on Clean Transportation</td>
</tr>
<tr>
<td>BEV</td>
<td>Battery Electric Vehicle</td>
<td>ICEV</td>
<td>Internal Combustion Engine Vehicle</td>
</tr>
<tr>
<td>CARB</td>
<td>California Air Resources Board</td>
<td>L1</td>
<td>Level 1 [Charger]</td>
</tr>
<tr>
<td>CEC</td>
<td>California Energy Commission</td>
<td>L2</td>
<td>Level 2 [Charger]</td>
</tr>
<tr>
<td>DCFC</td>
<td>Direct Current Fast Charger</td>
<td>LD</td>
<td>Light Duty</td>
</tr>
<tr>
<td>DOE</td>
<td>Department of Energy</td>
<td>MCS</td>
<td>Megawatt Charging System</td>
</tr>
<tr>
<td>EIA</td>
<td>Energy Information Administration</td>
<td>MD</td>
<td>Medium Duty</td>
</tr>
<tr>
<td>EPA</td>
<td>Environmental Protection Agency</td>
<td>MDHD</td>
<td>Medium- and Heavy-Duty</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MT/MMT</td>
<td>Metric Tons/Million Metric Tons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>MOVES</td>
<td>Motor Vehicle Emission Simulator Tool</td>
</tr>
<tr>
<td></td>
<td></td>
<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
</tr>
</tbody>
</table>
Get in touch with us:
Stephanie Kong
Senior Manager, Transportation Electrification
(909) 294 0373
Stephanie.Kong@icf.com

About ICF
ICF (NASDAQ:ICFI) is a global consulting and digital services company with over 7,000 full- and part-time employees, but we are not your typical consultants. At ICF, business analysts and policy specialists work together with digital strategists, data scientists and creatives. We combine unmatched industry expertise with cutting-edge engagement capabilities to help organizations solve their most complex challenges. Since 1969, public and private sector clients have worked with ICF to navigate change and shape the future.