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NEAR-TERM INFRASTRUCTURE DEPLOYMENT TO SUPPORT ZERO-EMISSION MEDIUM- AND HEAVY-DUTY VEHICLES IN THE UNITED STATES

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EXECUTIVE SUMMARY

The electrification of medium- and heavy-duty vehicles (MHDVs) is gaining momentum in the United States, and the major manufacturers in the country have made ambitious commitments for the mass production of zero-emission vehicles (ZEVs) as early as 2030. State-level regulations such as California's Advanced Clean Trucks (ACT) rule, federal incentives in the Inflation Reduction Act, and the U.S. commitment to join the Global Commercial Drive to Zero (aimed at 100% ZEV sales by 2040) are increasing ZEV adoption in the MHDV sector. Electrifying transportation nationwide will require the deployment of charging (for battery electric vehicles) and refueling (for hydrogen vehicles) infrastructure, as well as the supporting electrical grid infrastructure. MHDV fleet operators, electric utilities, and policymakers alike are uncertain as to where, how much, and by what year charging and refueling infrastructure needs to be built, and what upgrades to grid infrastructure are required to enable this deployment.

This paper addresses those uncertainties by assessing the near-term charging and refueling infrastructure needs for Class 4-8 MHDVs at both national and sub-national levels. We estimate MHDV charger needs in 2025 and 2030 based on projections of near-term ZEV market growth, and identify priority locations for the deployment of charging and refueling infrastructure in the near term. We identify the industrial areas expected to experience the highest electrical load from MHDV charging in the next 7 years and suggest targets for the deployment of high-power charging stations along key freight corridors across the country. Model results are complemented by insights from stakeholders in zero-emission-MHDV charging who shared key challenges and potential solutions to address them to enable the level of infrastructure deployment required. We propose a set of options for the diversity of stakeholders involved to enable charging infrastructure deployment, based on current and future grid capacity.

In the near term, a few U.S. states are expected to experience the highest energy needs from MHDV charging. Those include states that have adopted California's ACT rule (California, Colorado, Massachusetts, New Jersey, New York, Oregon, Vermont, and Washington), which provides strong regulatory support for the electrification of MHDVs, as well as states with the largest industrial activity (including Florida, Illinois, and Texas). We project California and Texas alone will account for a combined 19% of MHDV energy needs in 2030. Within those states, charging needs will be concentrated in a few industrial areas and along freight corridors that connect them.

Figure ES1 shows the 2030 energy consumption from MHDV charging at the county level, based on projections of near-term ZEV market growth. Darker colors correspond to counties with higher absolute charging needs from the MHDV fleet (in megawatt-hours per day), while the labels highlight the ten counties with the highest absolute energy needs. We find that near-term energy needs will be concentrated in industrial areas in the largest metropolitan areas in the country, including Los Angeles, Phoenix, Houston, Chicago, and Dallas. 1% of U.S. counties will account for 15% of nationwide MHDV charging energy needs in 2030, constituting high-priority areas in which to concentrate near-term deployment of charging and refueling infrastructure for MHDVs. Counties containing New York City, Boston, and Philadelphia will experience the highest energy consumption per unit area.

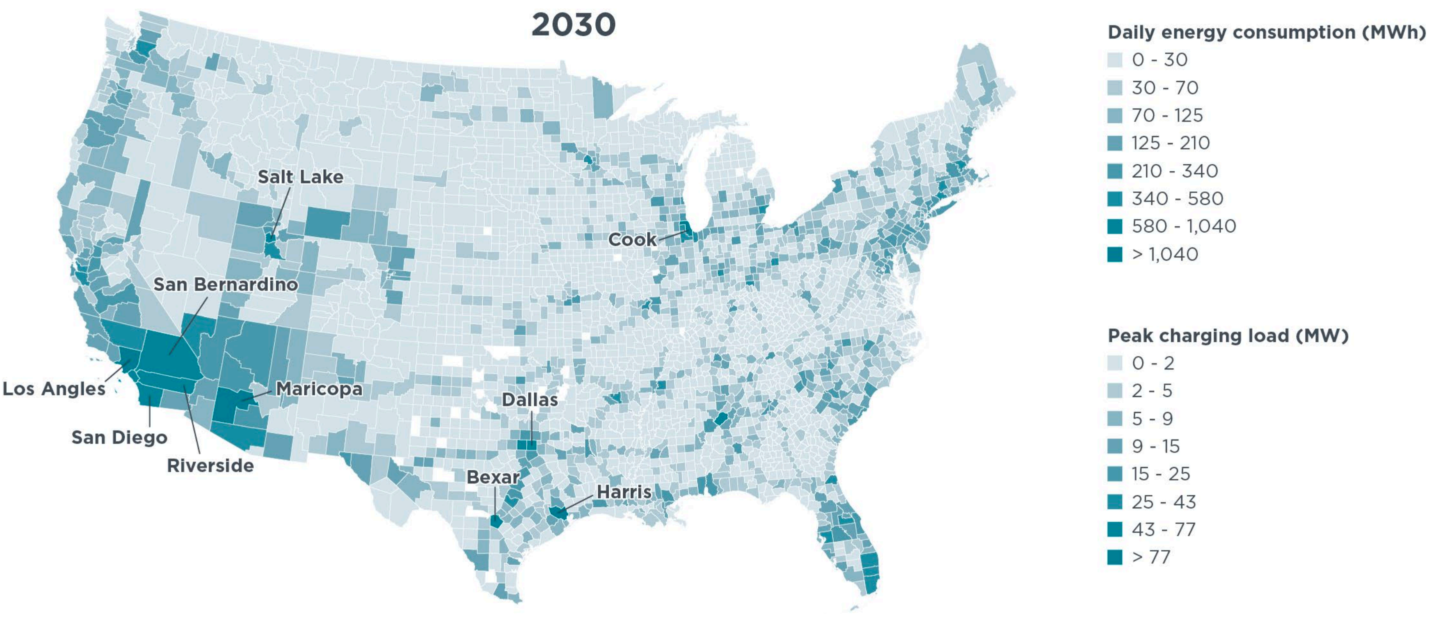

Figure ES1. County-level electric MHDV daily energy consumption in 2030 based on projections of near-term ZEV market growth (data labels indicate the ten counties with the highest energy consumption from electric MHDV).

The corridors of the National Highway Freight Network (NHFN) are projected to comprise 85% of the charging needs from long-haul trucks by 2030. Those needs can be met by setting targets for the capacity of charging stations located, on average, every 50 miles along the NHFN in line with the Federal Highway Administration's alternative fuel corridor designation criteria for light-duty vehicle charging. Table ES1 shows the ICCT's assessment of the resulting station capacity requirements to meet energy need projections. Stations with capacity up to 14 MW will be needed by 2030. In practice, flexibilities to the 50-mile requirement should be introduced to account for grid capacity and land availability. MHDV charging along highways also requires additional considerations to accommodate the parking and accessibility needs of those larger vehicles.

Table ES1. Minimum size of public charging stations every 50 miles along the NHFN to support long-haul trucks

Percentile of annual average daily traffic count on the NHFN	2025 minimum station size	2030 minimum station size
0 – 25%	350 kW/station	1,900 kW/station
25% – 50%	400 kW/station	4,300 kW/station
50% – 75%	700 kW/station	7,200 kW/station
>75%	1,400 kW/station	13,500 kW/station
NHFN national average	**600 kW/station**	**6,200 kW/station**

Note: This table was updated on May 23, 2023 to accurately reflect modeling assumptions.

By 2030, MHDV electrification is projected to increase the U.S. daily electric energy consumption by 140,000 megawatt-hours per day. This equates to around 1% of the total national electricity retail sales in 2021, representing a marginal increase in required electric power generation. On the other hand, high-energy demand counties are expected to experience high loads for MHDV charging of up to 132 MW, which will concentrate in locations where fleets congregate. At the same time, we project utilities should plan for nameplate capacities aggregating to up to 1,000 MW at the county-level, which corresponds to the aggregated power of all chargers being used simultaneously. These power levels require appropriate planning and early capacity building to accommodate for future transmission and distribution needs, as grid upgrades usually involve long lead times. Interviews conducted with charging infrastructure stakeholders highlighted other challenges faced by MHDV fleets that are planning for electrification, including balancing between depot and en route charging, unique considerations for rural infrastructure, and the complexity of accessing infrastructure incentives.

To address those uncertainties, we identify a set of options to make the best use of existing grid capacity and plan for future capacity building. These options target utilities and their regulatory bodies, local and state agencies, MHDV fleets, and vehicle manufacturers. There are immediately actionable options that do not require regulatory approval, including smart charging, load rebalancing, and making use of non-firm distribution grid capacity. In parallel, existing policy frameworks and practices need changes to enable utilities to incorporate projections of future charging loads when planning for future near- and long-term grid capacity building. Policy-enabled options include pre-build construction of grid capacity in “no-regret” zones and connecting MHDV charging loads to higher-voltage portions of the grid.

From our modeling results and discussions with stakeholders, we draw the following conclusions:

» **U.S. heavy-duty charging infrastructure does not all need to be built at once.** A few counties in key states are expected to concentrate a significant share of energy needs in the next decade. Targeting investments and policy support to priority areas can effectively support rapid ZEV deployment.

» **Our projections of MHDV energy needs are likely to materialize in states that have adopted the ACT, but likely constitute upper bounds for other states.** Our projections of ZEV market growth are based on the economic potential resulting from federal incentives and are applied nationwide. While states that have adopted the ACT have strong regulatory support to realize this potential, the outcome of those incentives on ZEV penetration is more uncertain in other states like Florida, Illinois, and Texas.

» **Setting targets for charging station deployment along key NHFN corridors can accommodate up to 85% of long-haul charging needs by 2030.** As such, those freight corridors constitute priority areas for infrastructure deployment. Long-haul trucks are projected to account for 21% of nationwide charging needs by 2030 (and a growing share beyond that as that segment of the market develops).

» **Electric utilities should plan for the significant loads that will come from electric MHDVs and provide timely interconnections.** Loads of up to 132 MW are expected at the county level by 2030; these will increase significantly beyond 2030. Given the long lead times involved in upgrading electric transmission and distribution systems, capacity building should start as soon as feasible. Upgrades on a project-by-project basis are unlikely to meet future needs. Rather, investments must be made at scale and at strategic locations suitable for, or likely to experience, MHDV charging. Electric utilities should revise their projections of expected loads from MHDV electrification to align with the latest ZEV market and policy developments.

» **There are many options to meet both near- and long-term charging needs.** In some locations, depending on available infrastructure, utilities may be able to meet some portion of near-term charging needs under current conditions or with the help of load rebalancing. Some stakeholders are ready and eager to take on MHDV charging. Utilities, regulators, other local and state agencies, original equipment manufacturers (OEMs), and fleets can begin collaborating today to set in motion regulatory and legislative changes, such as pre-build authorization in "no regrets" zones to enable the proactive buildout of infrastructure to serve the rapid growth of electric MHDVs in decades to come.

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INTRODUCTION

To achieve deep decarbonization goals and move toward its nationally determined contribution (NDC) as established in the Paris Climate Agreement, the United States must pursue ambitious greenhouse gas (GHG) emission reductions in the transportation sector, particularly within the medium- and heavy-duty vehicle (MHDV) segment.

State-level regulations are paving the way for the transition by setting zero-emission vehicle (ZEV) targets for MHDVs. California's Advanced Clean Trucks (ACT) rule, which has also been adopted in Massachusetts, New Jersey, New York, Oregon, Vermont, and Washington, requires ZEVs to comprise increasing percentages of MHDV sales. It sets sales requirements of 40% for tractor trucks and 75% for vocational vehicles by 2035 (Buysse & Sharpe, 2020). Original equipment manufacturers (OEMs) such as Daimler, Ford, and Navistar have set similarly ambitious zero-emission sales targets for their regional and global markets (ICCTb, 2022).

In November 2022, the United States joined 25 other countries in a Memorandum of Understanding under the Global Commercial Vehicle Drive to Zero, pledging to pursue 30% zero-emission MHDV sales by 2030 and 100% by 2040 (Global Commercial Drive To Zero, 2022). While these targets are not enshrined in binding regulation, the Phase 3 GHG regulation for heavy-duty vehicles currently under development by the U.S. Environmental Protection Agency (EPA) could speed the deployment of ZEVs. The Inflation Reduction Act and Bipartisan Infrastructure Law also enable accelerated ZEV adoption and the deployment of a robust network of supporting infrastructure (White House 2022.; Federal Highway Administration, 2023).

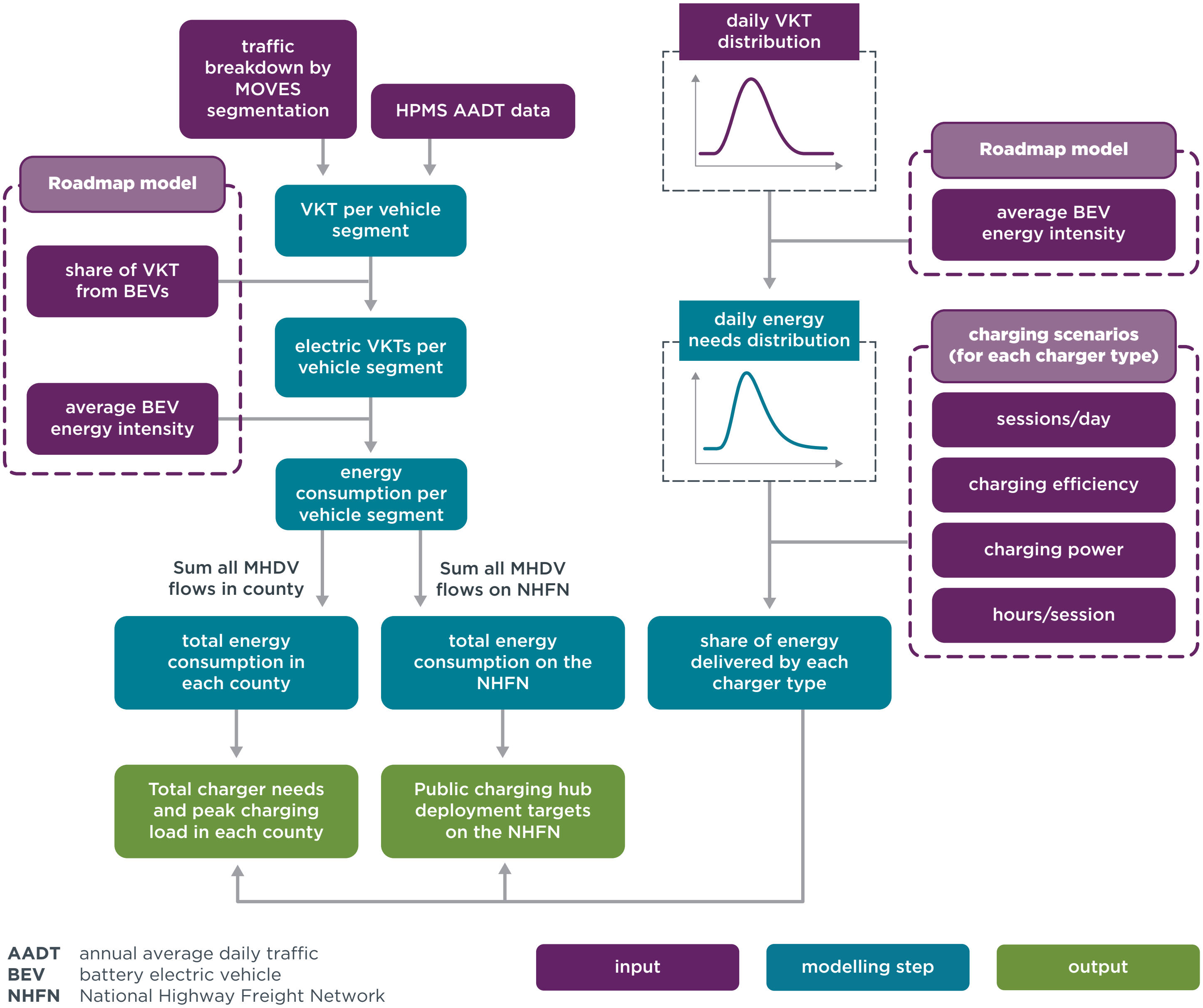
A timely deployment of charging and refueling infrastructure is required to support a nationwide fleet of zero-emission MHDVs, particularly in key industrial areas and along transportation corridors. To enable this deployment, fleets, electric utilities, and policymakers must work together to plan for the level of generation, transmission, and distribution capacity required for MHDV charging. Most uncertainties regarding infrastructure buildout concern the capacity of distribution systems to bring that energy to the right place in a timely manner and accommodate for the highly localized power requirements of MHDV charging.

This paper addresses these uncertainties by assessing charging and refueling infrastructure deployment needs for Class 4–8 MHDVs at the national and sub-national levels. We estimate the number of MHDV chargers required in the near term (2025 and 2030) and suggest key locations for early infrastructure deployment to support the growing ZEV market. We identify areas expected to see the highest electrical load from MHDV charging in the next 7 years and suggest targets for the deployment of high-power charging stations along key freight corridors. We pair modeling analysis with stakeholder interviews to explain the practical considerations required for such ambitious levels of infrastructure deployment and identify options to enable that deployment.

MODELING METHODS AND ASSUMPTIONS

MODELING MHDV CHARGING AND HYDROGEN REFUELING STATION NEEDS

To assess nationwide charging and refueling infrastructure needs through 2050, we build upon methods described in Minjares et al. (2021). We extend our analysis to all MHDV segments, perform additional analysis of truck flows in the United States to map the energy demand from zero-emission MHDVs, and identify key locations for public infrastructure deployment. Figure 1 illustrates the overall methodology. Key modeling steps and assumptions are further detailed in the following sections.



AADT	annual average daily traffic
BEV	battery electric vehicle
NHFN	National Highway Freight Network
VKT	vehicle kilometers traveled

Figure 1. Modeling method to assess nationwide charging and refueling needs.

ZEV deployment assumptions

We use the ICCT's Roadmap model to project ZEV deployment and stock turnover for MOVES categories of Class 4–8 MHDVs (ICCTa, 2022; EPA, 2020). Assumptions regarding ZEV deployment are based on scenarios developed in Ragon et al. (2023) to inform policy options for the EPA's Phase 3 greenhouse gas (GHG) emission standards for heavy-duty vehicles. We assume that near-term ZEV deployment through 2030 follows ambitious yet achievable projections based on current market developments. We consider the potential market growth that could result from ZEV production commitments by major truck manufacturers and policy incentives, and consider projections in the reduction of ZEV total cost of ownership (TCO) in line with the moderate estimate in Slowik et al. (2023). This corresponds to a ZEV sales share for Class 4–8 MHDVs of 39% in 2030, resulting in a stock of 1.1 million ZEVs—including 130,000 combination trucks, such as tractor-trailers—or 10% of the total MHDV stock.

Figure 2 shows the resulting ZEV stock and stock share projections through 2050. A more detailed explanation of the scenario can be found in Ragon et al. (2023) and specific data are included in the appendix.

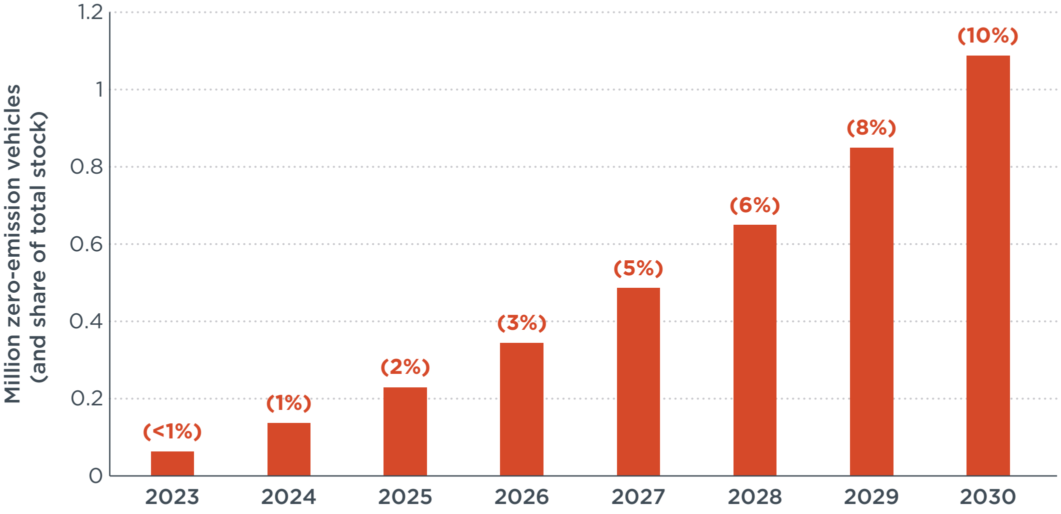


Figure 2. Stock and stock share of Class 4–8 zero-emission MHDVs through 2030, based on projections of near-term ZEV market growth. Percentage data labels represent the ZEV share of the total vehicle stock.

Technology mix modeling

We investigate infrastructure needs for two decarbonization technology pathways: battery electric vehicles (BEVs) and hydrogen vehicles, which includes both fuel cell electric vehicles (FCEVs) and hydrogen internal combustion engine vehicles (H_2-ICEVs), assuming both share the same refueling infrastructure. E-fuels are another full decarbonization pathway; however, ICCT analysis estimates that the high production costs of the most common type of e-diesel would make it prohibitively expensive as a drop-in fuel for road transport (Zhou, Searle, & Pavlenko, 2022). Biofuels are also not considered in this analysis as we judge they have limited potential for large scale decarbonization of MHDVs due to limited feedstock availability (Carraro, Searle, & Baldino, 2021).

The ICCT's most recent TCO analysis for the United States shows no case of positive TCO for hydrogen trucks relative to battery-electric trucks, even in a case with charging costs as high as $0.25/kWh and hydrogen prices as low as $8/kg (Basma et al., 2023). More details on hydrogen price projections and resulting market penetration projections are in the appendix. We do not project electricity prices in this study. Based on those results, the main results section of this report presents charging infrastructure needs assuming all ZEVs are battery-electric through 2050. Our projections of charging needs and the resulting charging infrastructure deployment requirements, therefore, represent an upper bound. The technology mix we assume is sensitive to future variations in energy prices.

We recognize that hydrogen trucks are an attractive solution for some use cases for which BEV charging poses significant operational challenges to fleets. In those cases, technology choices might be driven by operational constraints rather than TCO. Additionally, hydrogen prices could drop significantly lower than our projections with sufficient investments in research and development (Department of Energy, 2020). Therefore, we also perform a sensitivity analysis to assess hydrogen refueling needs with different levels of penetration of hydrogen in long-haul trucks. We estimate the sales share of hydrogen long-haul combination trucks that would result in a lower TCO if median hydrogen prices were to decrease from our central estimate of $9/kg to $5/kg (with prices as low as $3.5/kg) and assess the resulting nationwide needs for hydrogen refueling stations. Our price modeling assumes on-site production of renewable electrolysis hydrogen (Slowik et al., 2023). We provide nationwide hydrogen station needs but do not attempt to identify deployment locations or by how much the need for charging infrastructure would be reduced.

Mapping of energy needs based on traffic data analysis

We use traffic data from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System (HPMS) to map the MHDV fleet's energy needs onto the U.S. road network in the 48 continental states and the District of Columbia (FHWA, 2018). HPMS data is not available for Alaska; the data for Hawaii and Puerto Rico could not be calibrated against FHWA state totals, so we excluded those jurisdictions. The HPMS records 2018 annual average daily traffic (AADT) data for both combination and single-unit trucks on most public roads in each U.S. state. We convert the segment-specific traffic flow into vehicle miles traveled (VMT) by multiplying the AADT on each road section by the section length. We further break down the combination and single unit VMT data and attribute it to MHDV segments using MOVES population and activity data for different road types (see appendix) (EPA, 2020; ICCT, 2022).

Our modeling is sensitive to the quality of the HPMS AADT data and its associated data collection efforts. Therefore, we use information on the total annual VMT for each state from the FHWA to calibrate the traffic data (FWHA, 2019a; 2019b). We estimate that the HPMS data only covers about 74% of single-unit truck activity and 88% of combination truck activity. We calibrate it so that state totals match the state-wide aggregated FHWA data, in line with previous ICCT analysis (ICCT, 2022). For the remainder of the analysis, vehicle miles are converted to vehicle kilometers traveled (VKT).

The HPMS segments roads into sections of varying lengths, ranging from a few hundred meters to several kilometers. To enable easier handling of the geospatial data, we perform a grid transformation and apply the VKT from each road section to a single node located at its geographic center. Since most road sections are short in length and long road sections usually have very low traffic levels, this simplifying assumption results in little loss in accuracy. Figure 3 shows an example of the resulting grid for California.

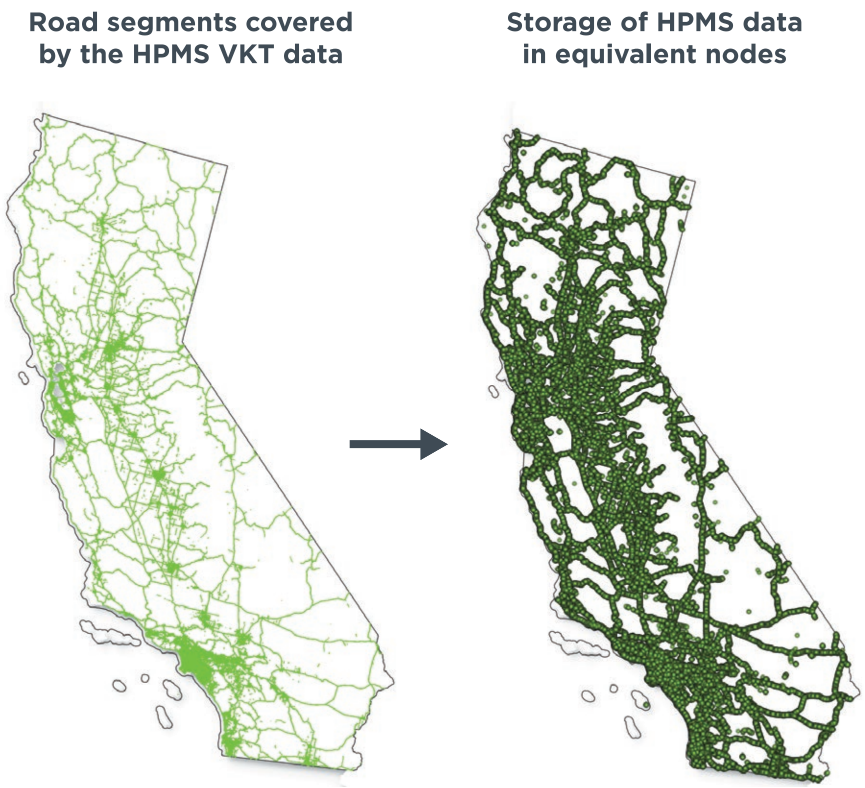


Figure 3. Example mapping of HPMS traffic and VKT data onto road segments (left) and nodes (right) for California.

We use these ZEV penetration projections to calculate the share of VKT performed by electric vehicles—hereafter referred to as eVKT. Finally, to obtain energy consumption, we multiply eVKT by the average ZEV energy consumption for each MHDV segment (in kWh/km). The average energy consumption accounts for new vehicle energy consumption, technology improvements through 2030 (in line with Basma et al., 2023), and fleet renewal over time. The ZEV energy consumption values assumed in this study are in the appendix.

Vehicle use cases and activity

Energy consumption is modeled based on segment-specific vehicle activity and technical characteristics. We estimate MHDV daily VKT based on Borlaug et al. (2022) for combination trucks, and on data from the National Renewable Energy Laboratory's Fleet DNA project for all other trucks and buses (Walkowicz, Duran, & Burton, 2022). Single unit long-haul mean daily VKT is set at 322 km (200 miles), which is the MOVES cutoff between short- and long-haul vehicles. Motor homes are excluded from this analysis as we model no ZEV penetration in this segment by 2030. Current and future vehicle energy intensity values for each vehicle category and powertrain type (BEV or FCEV) are obtained from Basma et al. (2023). Further technical characteristics and energy intensity data are in the appendix.

Daily VKT and energy consumption (calculated from the product of VKT and energy intensity) are assumed to follow a lognormal distribution, as shown in Figure 4 for each MHDV segment. We use energy demand distributions to assess the share of each charger type needed for each MHDV segment. However, total activity data and energy demand is informed by the HPMS data analysis.

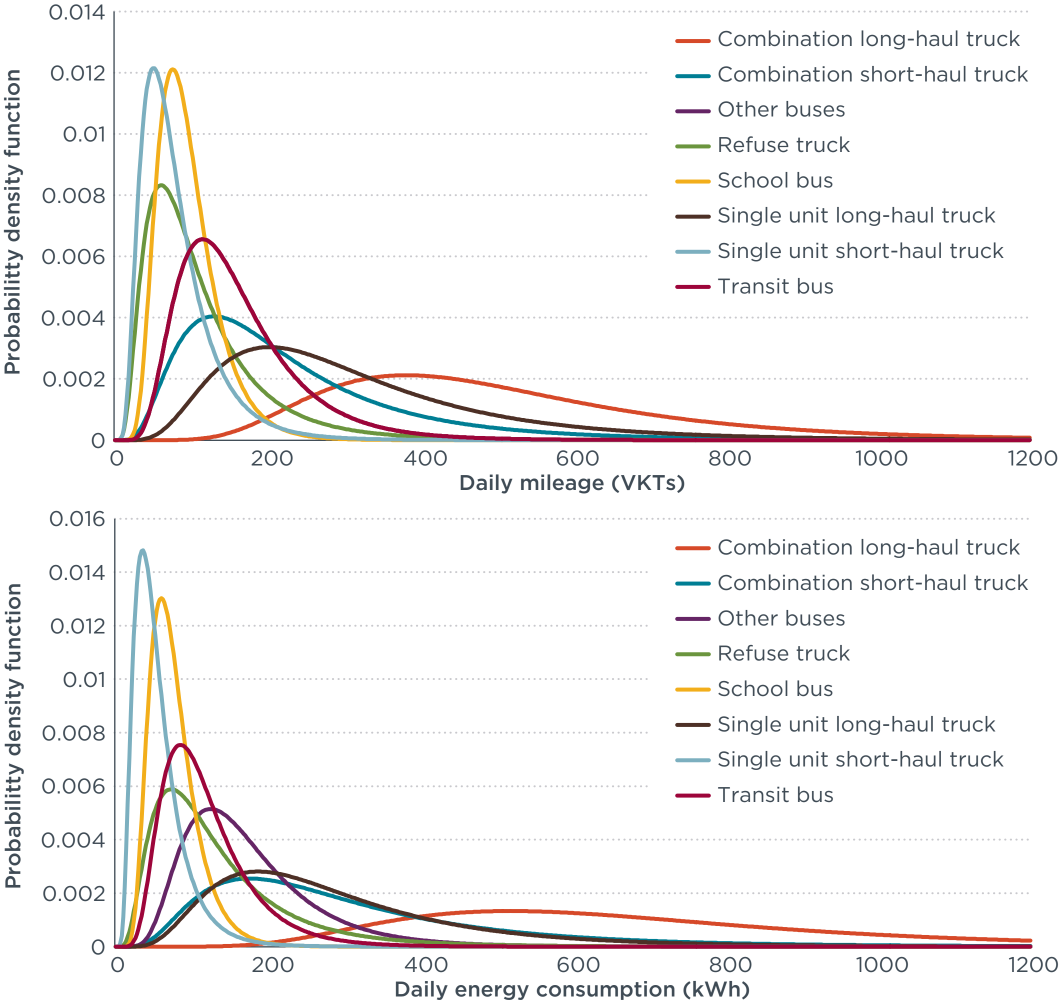


Figure 4. Probability density functions of daily VKT (top) and 2030 daily energy consumption (bottom) for all MHDV segments.

Charging and refueling characteristics

Several charging solutions exist for battery electric trucks, including stationary wired charging (i.e., charging stations), electric road systems with overhead catenary systems, and battery swapping (Rajon Bernard et al., 2022). We only consider stationary wired charging in this study, to reflect industry developments in the United States. We model charging behaviors to represent the average U.S. fleet for each MHDV segment. In practice, however, truck use cases can vary greatly within each segment; some fleets experience specific operational constraints that mandate different charging behaviors.

We assume all fleets maximize the use of overnight charging—either at depots or, in the case of long-haul trucks, public charging locations—to minimize the cost of charging. Charging overnight at a lower power than required for opportunity charging enables access to cheaper electricity rates (Basma et al., 2023). Overnight charging sessions are assumed to last up to 8 hours, with a nominal power of up to 150 kW. While some fleets experience operational constraints that do not enable such long dwell time, most MHDV batteries can be fully charged in significantly less than 8 hours. To reduce the cost of charging, trucks with smaller batteries can charge overnight with 50 kW CCS chargers or 19 kW Level 2 chargers in some cases, depending on the operational constraints faced by fleets. Table A4 in the appendix lists the average nominal overnight charging power required for each segment to fully recharge a battery with an 8-hour charging session. We assume all trucks start their operational day with a full battery. Segment-specific battery capacities are in the appendix, and we assume a 20% state of charge (SOC) reserve, so that batteries operate between 15%–95% SOC.

Remaining energy needs are provided by opportunity charging. We assume a combination of fast charging with combined charging standard (CCS) chargers and ultra-fast charging with megawatt charging standard (MCS) chargers that minimizes the number of MCS chargers needed, as they result in higher charging costs. CCS chargers can provide up to 350 kW of charging power. The MCS standard, which is still under development, is designed to provide up to 3.75 MW and, based on discussions with industry stakeholders, we assume typical MCS chargers in the United States will be designed to provide up to 2 MW of charging power. We assume large-scale commercialization of MCS chargers will start in 2027, in line with Basma et al. (2023). Opportunity charging sessions can vary in length based on energy requirements and are limited to 30 minutes due to our general assessment of operational constraints.

Opportunity charging can occur at a variety of locations, including depots, warehouses, logistic hubs, and public stations in industrial areas and along freight corridors. In the short term, MHDV fleet owners told us in interviews that they expect to rely more heavily on private charging, given the uncertain pace of deployment of public charging hubs. However, as the network of public charging stations grows, it can provide a convenient charging option for fleet owners, eliminating the need to invest in privately owned chargers. Therefore, we assume a mix of public and private charging, specific to each MHDV segment (see appendix).

Assumptions on infrastructure utilization are updated from Minjares et al. (2021), based on discussions with an MHDV charging point operator. Utilization starts at relatively low levels and grows as a function of the ZEV stock deployment. For overnight depot charging, we assume the availability of one charger per vehicle through 2050. For public overnight chargers, utilization starts at one session per day, assuming chargers will be used as soon as they become available. We assume these chargers will also be used for day charging during long dwell periods, increasing the utilization rate to 1.5 sessions per day in 2040, by which time we assume the market will be fully developed. Finally, the utilization of opportunity chargers increases from one session per day in 2023, to eight sessions per day in 2040. Table 1 summarizes our assumptions regarding charging characteristics.

Table 1. Characteristics of charger types for electric MHDVs in the United States

Charger type	Nominal power	Connector standard	Available for large-scale commercialization	Length of charging session	2023 sessions/day	Max sessions/day
Overnight	50–150 kW	CCS	<2023	up to 8h	1	1–1.5
Opportunity fast	350 kW	CCS	<2023	up to 0.5h	1	8
Opportunity ultra-fast	2 MW	MCS	2027	up to 0.5h	1	8

Note: Nominal power refers to the maximum power rating of the charger, but charging sessions can occur at a lower power level.

From those assumptions, we calculate the share of energy provided by each charger type for each MHDV segment, based on methods detailed in Ragon et al. (2022) (see Table A3 in the appendix). Figure 5 shows an example of the minimum combination of charging events required to meet the energy needs of a combination long-haul truck in 2030.

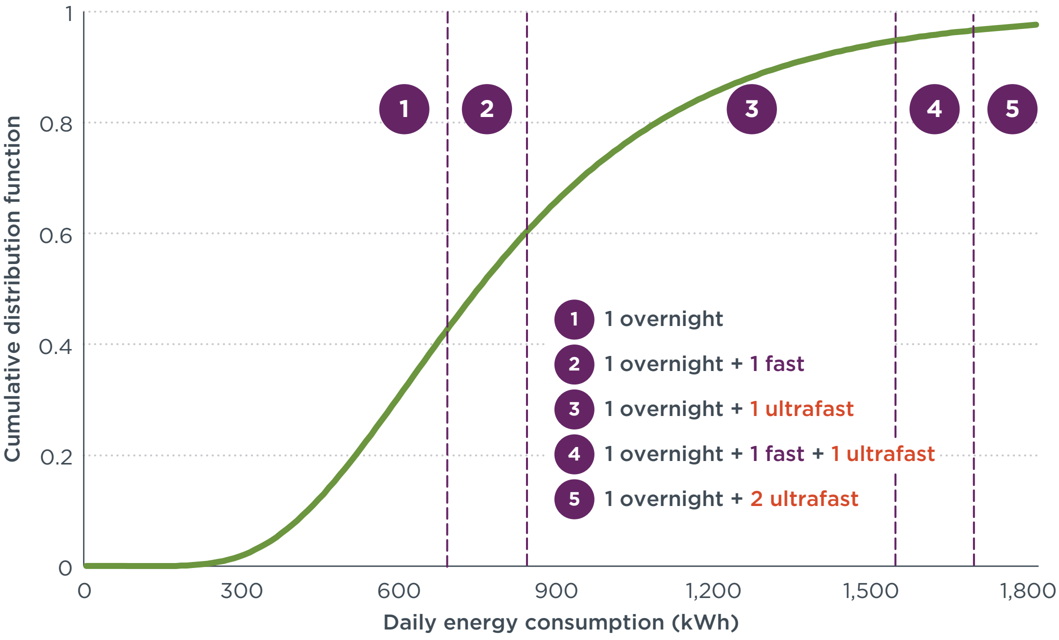


Figure 5. Cumulative distribution function for the daily energy demand of a Class 8 combination long-haul truck and charging sessions needed to meet that energy demand. Each area numbered 1–5 corresponds to the combination of charging events required to satisfy the truck's daily energy demand.

For long-haul hydrogen trucks, we convert our projections of nationwide energy consumption into hydrogen capacity requirements based on the fuel's properties, assuming a cycle-average fuel cell stack efficiency of 45% in 2023, increasing to 50% in 2040 (Basma & Rodríguez, 2023). The total hydrogen capacity required to meet the fleet energy needs is then converted into the number of required stations, assuming on-site production of renewable electrolysis hydrogen capped at 500 kg per day per station, and an average utilization growing from 10% of the total capacity in 2023 to 75% of the total capacity in 2040 (Minjares et al., 2021; Slowik et al., 2023).

PRIORITY AREAS IDENTIFICATION

We use two geographical scopes to identify priority areas for charging infrastructure deployment: U.S. counties, which reflect areas with varying levels of industrial activity, and freight corridors connecting the main industrial hubs in the country.[1]

U.S. Counties

We assess the total daily energy consumption from all MHDV flows in each U.S. county and assess the charging and refueling infrastructure needed to satisfy that energy consumption. We use this as the basis to identify priority areas for early infrastructure deployment. Those counties will need the greatest support to quickly deploy MHDV charging stations, and electric utilities operating in those high-energy areas may need to upgrade local transmission and distribution systems. As such, we also estimate the required peak load utilities can expect from MHDV charging in high-priority counties, and the nameplate capacity of MHDV chargers that will connect to local transmission and distribution systems.

National Highway Freight Network (NHFN)

Freight corridors connecting large industrial areas are also expected to require significant charging infrastructure for long-haul and, to a smaller extent, regional-haul trucks. We use the NHFN as our framework of analysis for freight corridors (FHWA, 2020). We identify the required charging capacity of truck stops along key highways assuming truck stops are deployed at regular 50-mile intervals, in line with the FHWA's designation criteria for Alternative Fuels Corridors for light-duty vehicles.

We only capture the public charging needs of long-haul trucks, assuming they are the main truck type that will charge on highways.

PEAK CHARGING LOAD AND INSTALLED NAMEPLATE CAPACITY IN PRIORITY INFRASTRUCTURE DEPLOYMENT AREAS

To inform electric utilities in their transport electrification planning efforts, we provide an estimate of the peak power demand that can be expected from MHDV charging at the county level.

The distribution of charging needs throughout the day varies greatly from one fleet and vehicle segment to another based on specific operational constraints. To estimate this distribution, we use typical fleet load profiles from the Medium- and Heavy-Duty Electric Vehicle Infrastructure – Load Operations and Deployment (HEVI-LOAD) project led by Lawrence Berkeley National Laboratory, which is part of California Energy Commission's effort to plan for MHDV charging needs in California through 2030 (Wang et al., 2021). HEVI-LOAD projects charging patterns of different MHDV segments, considering energy market conditions, grid constraints, and fleet preferences.

Figure 6 shows the aggregated load profile for all Class 4–8 vehicles in 2030. The charging load is distributed throughout the day, reflecting a certain degree of diversity in charging patterns across fleets. Dwelling periods for depot charging can occur at different times of day, with a higher concentration at night; opportunity charging is likely to be distributed more evenly throughout the day. The HEVI-LOAD project

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[1] The U.S. Census Bureau considers independent cities as "county equivalents" (United States Census Bureau, 2021). For the purposes of this study, independent cities are referred to and treated as counties.

projects that the aggregated peak load in California will be 1.77 times higher than the average load and will occur between 01:00 and 02:00. While that peak represents a measure of the highest power requirement from MHDV charging, it might not be the most challenging for utilities to accommodate for, since it occurs when the load from other sources will be low. The 125% peak occurring at 17:00 may be more challenging due to concurrent demand from other sources.

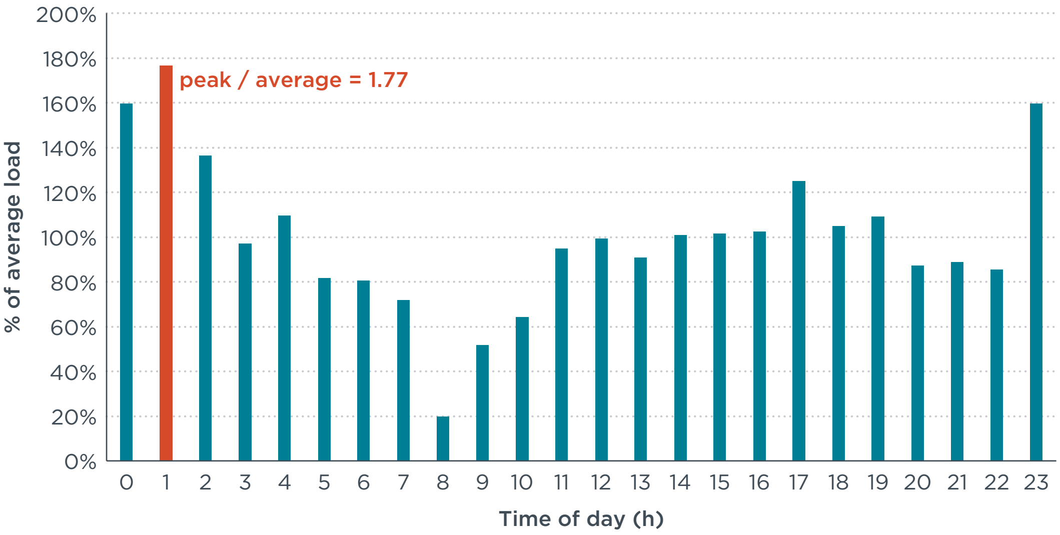

Figure 6. Typical fleet charging load profile for Class 4–8 MHDVs in California in 2030.

We apply the 1.77 ratio to the average power consumption in a county, obtained by dividing the total daily energy consumption by 24 hours, to estimate the maximum load counties will experience from MHDV charging. To plan for the worst-case scenario, utilities can assume that those peak load estimates will occur at the busiest time of day. Importantly, this peak load analysis does not attempt to capture the benefits of managed charging or load management techniques, such as smart charging or load rebalancing, which have the potential to considerably reduce the required peak load capacity (National Renewable Energy Lab, 2020).

Additionally, when providing new electrical connections, utilities must ensure that the distribution systems are able to deliver the combined nominal power from all connected loads at any given time, plus a buffer, to cover for the unlikely case that all loads would draw power from the grid simultaneously. The installed nameplate capacity of chargers on the local distribution grid is, therefore, typically much higher than the expected peak load at any time. To inform nameplate capacity installations in each county, we also consider a worst-case scenario where all MHDV chargers are being used at the same time, drawing power from the grid at their respective nominal powers. The nominal power is 350 kW for fast chargers, 2 MW for ultrafast chargers, and varies across segments for overnight charging (see Table A3 in the appendix). When attributing charger sizes to each segment, we assume, based on discussions with industry representatives, that fleets will install overnight chargers that are larger than strictly needed to fully charge their trucks overnight to give them the flexibility to charge at a high power if desired. This is reflected in our assessment of nameplate capacity, but does not affect the peak charging load analysis, since fleets are assumed to only draw the minimum required power from those chargers.

TARGET SETTING FOR PUBLIC CHARGING INFRASTRUCTURE DEPLOYMENT

Since 2015, the FHWA has designated roads as Alternative Fuel Corridors (AFCs) to guide the deployment of charging and alternative fuel (hydrogen and natural gas) refueling infrastructure, mostly for light-duty vehicles. Criteria for electric charging include that the maximum distance between two stations should not be more than 50 miles and stations should have at least four 150 kW charging points, amounting to a minimum power requirement of 600 kW per station. Those corridors closely follow interstate highways. The Bipartisan Infrastructure Law established the National Electric Vehicle Infrastructure program to provide funding for charging and refueling infrastructure on roads that meet AFC designation criteria.

To identify priority highways for MHDV charging, we propose targets for the deployment of public MHDV charging stations along the NHFN, following a method in line with previous ICCT analysis to inform Europe's Alternative Fuels Infrastructure Regulation (Ragon et al., 2022). There is significant overlap between AFCs and the NHFN, particularly for interstate highways, state highways, and U.S. routes. However, the NHFN also covers other public roads that are critical to freight traffic, many of which are not designated AFCs (FHWA, 2022). The FHWA encourages state agencies to nominate AFCs within the Interstate Highway System, and charging corridors are not differentiated between LDVs and MHDVs (Shepherd, 2022). Therefore, we focus on roads within the NHFN to maximize applicability to the MHDV sector.

For each road section of the NHFN, we estimate the required installed power of MHDV charging stations based on modeled energy needs, assuming the distance between two stations is 50 miles, in line with the AFC designation criteria. The feasibility of developing such a dense network of MHDV charging stations will depend on land and space availability. We aggregate the charging station power requirement from all road sections of the NFHN into four pools, which serve as the basis for our proposed priority targets.

NEAR-TERM CHARGING AND REFUELING INFRASTRUCTURE NEEDS

Based on the projected development of the ZEV market, we estimate electric MHDVs will consume 140,000 MWh of electric energy daily by 2030. To accommodate the energy needs of 229,000 electric MHDVs in 2025, 124,000 overnight chargers and 11,900 fast chargers will be needed nationwide (assuming MCS chargers only become available in 2027). By 2030, 522,000 overnight chargers, 28,500 fast chargers and 9,540 ultrafast chargers will be needed for 1.1 million electric MHDVs—representing 10% of the total vehicle stock. To help prioritize near-term infrastructure deployment, we identify key areas and freight corridors expected to have the highest energy demand for MHDV charging in 2025 and 2030 and assess the peak charging load that can be expected by utilities in these high-priority areas.

STATE-LEVEL PROJECTIONS OF ENERGY NEEDS FROM ELECTRIC MHDVS

The energy needs of MHDV charging are expected to grow most rapidly in the near term in states with the most industrial activity and strongest supporting ZEV policies. Our modeling of near-term ZEV market growth assumes uniform ZEV deployment nationwide, based on the economic opportunities introduced by state incentives in the IRA (Slowik et al. 2023). While this potential is likely to realize in states that have adopted California's ACT rule, other states have not implemented binding regulations to support this level of market uptake. Therefore, we estimate our projections for non-ACT states represent an upper bound for MHDV charging needs.

Our analysis shows that Texas will have the highest share of energy needs from MHDV charging in 2030 (11% of the U.S. total), followed by California (8%) and Florida (5%). Other states that have implemented the ACT rule rank 10 (New York) to 48 (Vermont) based on our projections, but they may experience a higher share of the national charging needs in 2030 due to additional regulatory support. Table 2 shows the total VKTs traveled by MHDVs in ACT states from FHWA along with our projections of eVKTs and energy consumption from MHDV charging in each state for 2030 (FHWA, 2022a). Results for non-ACT states are listed in Table A6 in the appendix. Ten states comprise half of the projected energy consumption from MHDVs in 2030.

Table 2. State total daily VKT, projected eVKT, and energy consumption from MHDV charging in ACT states in 2030

Rank in U.S.	State	Total daily VKT, Class 4–8 MHDVs (km)	Total daily eVKT, Class 4-8 MDHVs (km)	Daily energy consumption from charging (MWh)	Share of national energy consumption
2	**California**	180,728,114	23,719,908	11,196	8%
10	**New York**	50,770,266	6,923,440	4,231	3%
22	**Washington**	60,919,508	5,450,202	2,398	2%
25	**Oregon**	49,076,476	5,367,451	2,229	2%
26	**New Jersey**	43,720,773	6,348,471	2,047	1%
31	**Colorado**	42,265,662	5,098,477	1,849	1%
32	**Massachusetts**	48,185,397	6,862,962	1,732	1%
48	**Vermont**	1,909,384	212,349	276	0%
U.S. total		**3,523,436,176**	**399,077,768**	**139,865**	**100%**

Note: States are ranked in descending order of daily energy consumption.

KEY AREAS FOR NEAR-TERM CHARGING INFRASTRUCTURE DEPLOYMENT

The ten counties with the highest expected energy consumption from electric MHDVs (out of 3,079 nationwide) account for 8% of projected energy needs in both 2025 and 2030. The top 15 counties account for 11% of projected energy needs, and the top 30 account for 15%. Those counties contain some of the most industrialized areas in the country (e.g., Chicago, Dallas, Houston, Los Angeles, Phoenix). Figure 7 shows county-level daily energy consumption from electric MHDV charging in 2025 and 2030.

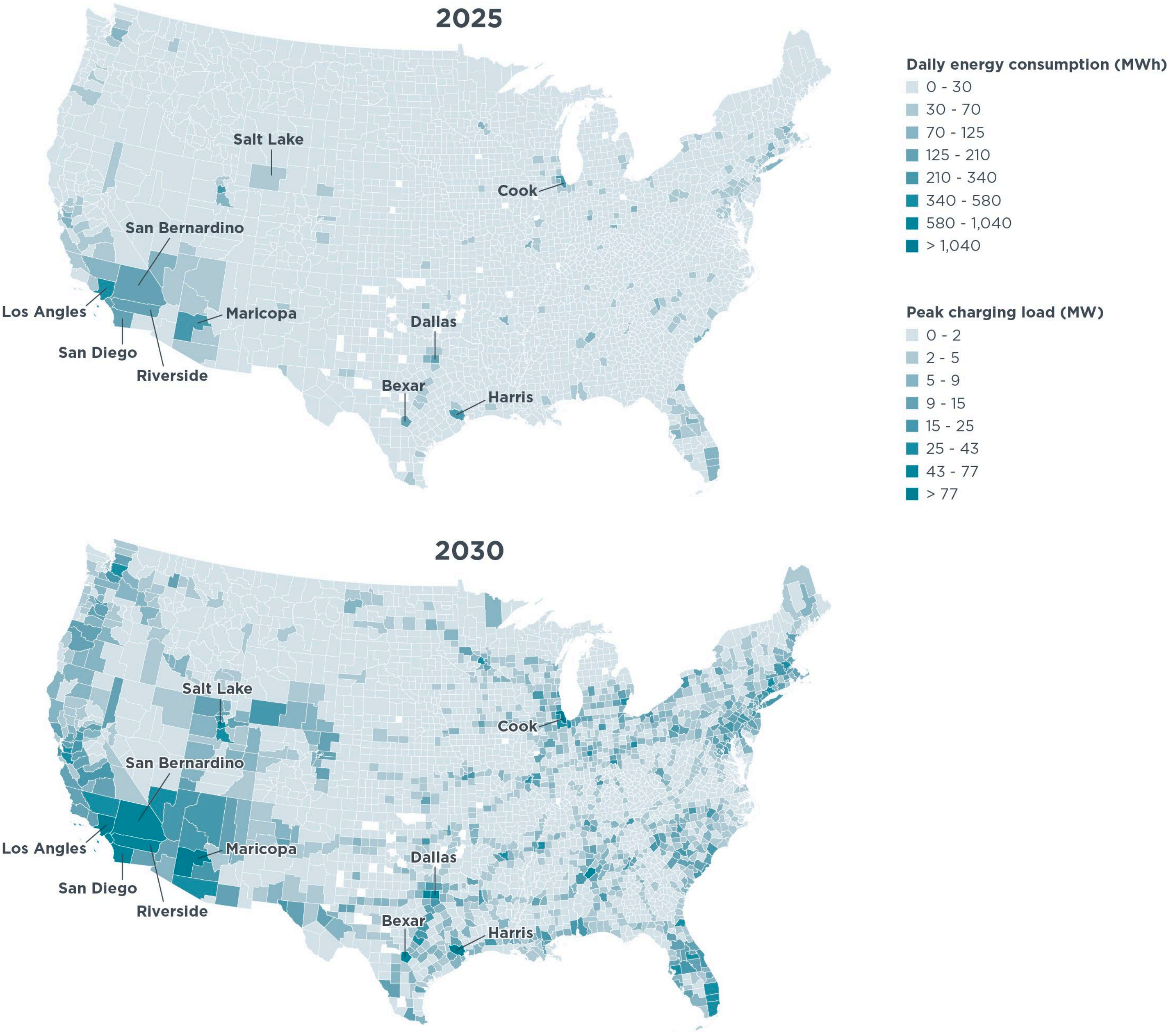

Figure 7. County-level projected electric MHDV daily energy consumption and estimated peak charging load in 2025 and 2030, based on projections of near-term ZEV market growth (data labels indicate the 10 counties with the highest energy consumption from electric MHDV charging in the United States in each year).

Some counties in the Northeast and Florida not highlighted in Figure 7 are also expected to experience high concentrations of MHDV charging, but those counties have smaller areas resulting in a lower absolute energy consumption. When ranking counties by energy consumption per unit area, five of the top six are in New York State (see appendix). Some counties—including Orange County in California, Dallas County and Harris County in Texas, and Cook County in Illinois—rank in the top 1% both in terms of absolute energy consumption and energy consumption per area.

The deployment of MHDV chargers should be prioritized in high energy consumption areas to support near-term ZEV market development. Table 3 shows the number of chargers, per charger type, needed to meet those energy needs in the 10 counties with the highest energy consumption from electric MHDV charging. Charger needs for the top 50 counties in 2030 are listed in the appendix.

Due to a high concentration of MHDV chargers, utilities operating in those counties are expected to experience relatively high charging loads, requiring careful management and capacity building. Table 3 also shows our projections of peak charging load, based on the typical Class 4–8 MHDV fleet charging profile in Figure 6. Additionally, Table 3 shows an estimate of the required nameplate capacity of all chargers on the local distribution grid in those counties for a case in which all chargers draw power from the grid simultaneously.

Table 3. Energy consumption, charger needs, peak charging load, and required grid capacity in the 10 U.S. counties with the highest projected energy consumption from electric MHDV charging in 2030

Rank	County	Daily energy consumption (MWh)	Estimated peak charigng load (MW)	Overnight chargers	Fast chargers	Ultrafast chargers	Nameplate capacity of chargers on local distribution grid (MW)
1	**Los Angeles, CA**	1,791	132	8,666	80	38	974
2	**Maricopa, AZ**	1,616	119	7,125	72	41	832
3	**Harris, TX**	1,613	119	7,036	72	41	826
4	**Cook, IL**	1,266	93	6,051	57	28	683
5	**Dallas, TX**	1,019	75	3,963	45	31	490
6	**San Bernardino, CA**	943	70	4,166	41	23	482
7	**San Diego, CA**	940	69	4,463	42	21	505
8	**Salt Lake, UT**	937	69	5,014	42	16	541
9	**Riverside, CA**	708	52	3,360	31	15	379
10	**Bexar, TX**	698	51	2,789	31	20	340
US total		**139,893**	**10,317**	**580,054**	**7,869**	**5,639**	**69,157**

Note: Counties are ranked in descending order of energy consumption. This table was updated on May 22, 2023 to accurately reflect modeling assumptions.

In general, counties with more long-haul truck flows, such as Dallas, Texas, will require a higher share of opportunity charging, and fleets will rely more heavily on publicly accessible charging stations along freight corridors. Counties with a high share of urban and regional trucking, such as Salt Lake County, Utah, will require a higher share of overnight charging more concentrated at depots in metropolitan areas. We assume no constraint on space availability for depot charging (i.e., all fleets that have access to depots can install overnight chargers).

We find that the top 10 counties would experience peak charging loads of 85 MW on average. Los Angeles County would experience loads up to 132 MW, and Maricopa

County (containing Phoenix, Arizona) and Harris County (containing Houston, Texas) would experience loads slightly under 120 MW. Additionally, transmission and distribution systems in those counties will need to accommodate nameplate capacities of 600 MW on average and up to 1,000 MW (Los Angeles County) for MHDV charging by 2030.

These high loads might require time sensitive upgrades to transmission and distribution systems. Given the long lead times involved in these types of projects, construction work should start as soon as possible in areas that offer a high degree of certainty on future energy needs from MHDVs. Other options to manage existing grid capacity are outlined later in this paper.

INFRASTRUCTURE NEEDS ALONG NATIONAL FREIGHT CORRIDORS

Additionally, we project energy needs along the NHFN to inform the deployment of public MHDV charging hubs along key freight corridors in the country. Figure 8 shows the projected energy consumption from electric long-haul trucks along the NHFN in 2030. We find that up to 85% of long-haul truck charging needs in the country will concentrate on the corridors of the NHFN in 2030. Deploying charging stations at truck stops along those corridors can, therefore, cover a significant portion of charging needs.

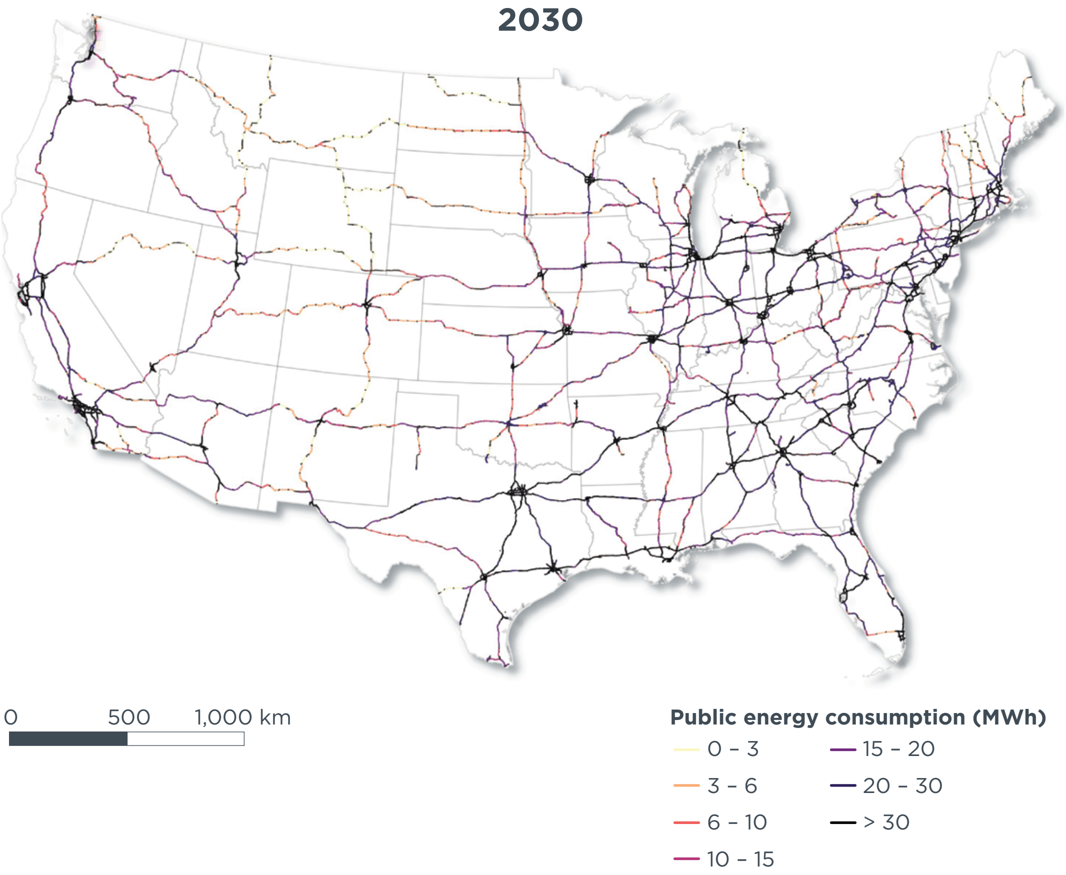

Figure 8. Daily energy consumption along the corridors of the NHFN in 2030, based on projections of near-term ZEV market development.

We assess the size, or installed power capacity, that would be needed for those charging stations, assuming an average distance of 50 miles between two stations, which aligns with FHWA's alternative fuel corridors designation criteria. With a total NHFN length of 50,600 miles, that would result in 844 charging stations nationwide. To meet total energy needs on the NHFN, charging stations would need to be equipped with chargers amounting to an average station size of 600 kW in 2025 and 6 MW in 2030.

To further prioritize infrastructure deployment along freight corridors, we assess the required size of charging stations to be deployed on the NHFN for different levels of electric MHDV activity. Table 4 summarizes the required station sizes for four pools of MHDV activity level, measured in annual average daily traffic counts from the HMPS data. Pooling is defined by the quartiles of the eVKT distribution along the freight corridors; station capacity targets are calculated from the average energy consumption within each quartile.

Table 4. Minimum size of public charging stations every 50 miles along the NHFN to support long-haul trucks

Percentile of annual average daily traffic count on the NHFN	2025 minimum station size	2030 minimum station size
0 – 25%	350 kW/station	1,900 kW/station
25% – 50%	400 kW/station	4,300 kW/station
50% – 75%	700 kW/station	7,200 kW/station
>75%	1,400 kW/station	13,500 kW/station
NHFN national average	**600 kW/station**	**6,200 kW/station**

Note: This table was updated on May 23, 2023 to accurately reflect modeling assumptions.

The peak charging load at each charging station is expected to be much lower than the specified station size, which represents the aggregated nominal power of all installed chargers. For public charging, it is unlikely that all chargers at a charging station would be used at their nominal power simultaneously, particularly in early years when relatively low infrastructure utilization is assumed. However, utilities will have to plan for the combined nameplate capacity of all chargers when updating local distribution and transmission grids.

The FHWA's alternative fuel corridor designation criteria for light-duty vehicles require that publicly accessible DC fast charging stations are deployed no more than 1 mile away from an interstate highway. However, to accommodate for parking space and grid capacity constraints, public charging station operators might choose to install stations up to a few miles away from main highways. According to discussions with an MHDV charging point operator, installing stations a few miles away from highways can also enable the integration of locally generated renewable energy.

HYDROGEN REFUELING STATION NEEDS

Our renewable hydrogen price projections of \$8/kg–\$10/kg in 2040 means there will be very few cases of lower total cost of ownership for hydrogen long-haul trucks over their battery-electric counterparts (Basma et al, 2023). Hydrogen trucks could become cost-competitive in the late 2030s, if hydrogen prices became significantly lower than our central estimate. However, even with median hydrogen prices as low as $3, we find no significant business case for hydrogen trucks before 2035 due to lower technology maturity.

Yet there is interest in hydrogen trucks (both FCEVs and H_2-ICEVs) as an alternative to battery electric trucks, because their higher driving ranges could limit the operational challenges associated with electric charging. Therefore, we assess the needs for hydrogen refueling infrastructure under hypothetical scenarios for hydrogen prices dropping significantly lower than the projected $9/kg in 2040. Energy consumption modeling is based on the technical characteristics of a combination long-haul FCEV, as shown in Basma et al. (2023).

Table 5 shows our projections of hydrogen truck penetration in 2050, nationwide daily hydrogen capacity requirements, and hydrogen station needs under three hydrogen price scenarios for 2040: $9/kg, $6/kg, and $5/kg. We project that, if median hydrogen prices were to drop to $6/kg in 2040, there could be 85,000 long-haul hydrogen trucks on U.S. roads by 2050, requiring a total of 7,500 refueling stations producing hydrogen from on-site renewable electrolysis. If median prices were to drop to $5/kg, a total of 250,000 long-haul hydrogen trucks would require 22,000 refueling stations.

Table 5. Hydrogen truck deployment and associated refueling needs under different hydrogen price scenarios

2040 H_2 price	2040 H_2 long-haul truck sales share	2050 H_2 long-haul truck stock	2050 Nationwide daily hydrogen capacity (metric tons)	2050 Nationwide H_2 stations
$9/kg	0%	0	0	0
$6/kg	9%	85,160	2,826	7,516
$5/kg	30%	246,955	8,195	21,795

ENABLING INFRASTRUCTURE DEPLOYMENT

The results presented in the previous sections show that 1% of counties will be responsible for approximately 15% of U.S. MHDV charging needs by 2030, demonstrating a need to accelerate infrastructure deployment in those areas in the near term. Planning to address near-term needs requires a robust understanding of the practical considerations of deploying charging infrastructure.

Maximum charging loads of over 100 megawatts can be expected at the county level; loads of several megawatts can be expected at the charging station or depot level. These charging loads may require costly and time-consuming upgrades to substations, transformers, power lines, and other distribution infrastructure, as well as to electrical panels and other behind-the-meter infrastructure at charging sites. Current permitting processes can add complexity and increase project costs. Depending on existing grid infrastructure and site-specific charging needs, upgrades could take several years to complete, while electric vehicles could be acquired relatively more quickly (CALSTART, 2020). Charging infrastructure deployment, therefore, requires careful planning by electric utilities and infrastructure project developers to optimize existing grid capacity and upgrade transmission and distribution systems ahead of demand.

Studies have found that parking and accessibility requirements, charging times, and transmission interconnections are key considerations for infrastructure deployment (American Transportation Research Institute, 2022; National Grid, 2022). The deployment of charging infrastructure requires the involvement of vehicle manufacturers, charging solution providers, electric utilities, regulators, landowners, site operators, and community stakeholders, particularly in lower income communities. Thus, project proponents must learn to navigate multilateral partnerships, the constraints of the electrical grid network, and the underlying policy and regulatory framework.

The next section explores practical challenges to infrastructure deployment as reported by a variety of stakeholders, while the following section provides options for all stakeholders to enable near- and long-term deployment.

THEMES FROM STAKEHOLDER INTERVIEWS

To explore known and potential challenges to infrastructure deployment for MHDVs, we interviewed ten stakeholders, representing government agencies, non-governmental organizations, port authorities, charging providers, and utilities. Table 6 provides a list of the interviewed organizations. Interviewees were selected to provide a wide range of perspectives on the deployment of charging infrastructure, from strategic policymaking and coalition building to on-the-ground considerations such as siting charging stations to optimize existing grid infrastructure.

Table 6. List of interviewed organizations

Organization	Organization type
Alliance for Transportation Electrification	Non-governmental organization
Amply Power	Charging provider
ChargePoint	Charging provider
Electric Power Research Institute	Non-governmental organization
Joint Office of Energy & Transportation	Government Agency
National Rural Electric Cooperatives Association	Utilities trade association
PG&E	Utilities
Port of Long Beach	Port authority
Port of Oakland	Port authority and electric utility
Renewable Energy Aggregators	Electricity generation and charging developer

Considerations for En-route charging versus depot charging

One charging provider representative noted that en route charging prioritizes convenience over cost. As MHDV drivers arrive at a charging station, they need to quickly authorize a payment and plug in their vehicles. Charging speed is critical to ensure drivers can get back on the road and continue to their next stop. Thus, opportunity charging necessitates high-powered, user-friendly stations that are optimized for throughput.

Depot charging is typically managed to minimize cost and maximize battery health. Charging may be delayed until off-peak hours to take advantage of cheaper electricity rates or slowed down to decrease battery degradation. Managed charging at depots can also allow for more flexible charging station arrangements where the maximum combined power rating of charging stations can exceed the power rating of the depot. For example, if a depot is rated for 600 kW, it need not limit itself to four chargers at 150 kW each. Additional 150 kW chargers can be installed, as long as there is charge management software to limit the total power drawn to 600 kW. Such a setup would be unsuitable for opportunity charging, where each station needs to be available to operate at full power.

Fleet operators looking to install a charging depot may also lease their land, making installation more difficult. One utility interviewee stated that tenants require easements from their landlords before lines can be placed in the ground. A previous ICCT study also highlighted the financial difficulties faced by small fleets in installing their own charging infrastructure (Brito, 2022).

Infrastructure incentives can be stackable but misaligned

As shown in this study, significant numbers of public and depot chargers, along with distribution and transmission infrastructure, will be needed to support electric MHDVs in the coming decades. Incentives are critical for kick-starting infrastructure deployment projects. However, due to the limited availability of public funds, incentive programs must be designed to minimize complications and avoid forestalling infrastructure deployment.

Incentive programs for charging infrastructure are administered at different levels of government and by different agencies. Certain incentives can be “stacked,” meaning that a project proponent may be eligible to receive funding from federal, state, and utility programs for the same project. While this improves the financial viability of installing infrastructure, it introduces complications as each program may be administered differently.

Charging provider representatives remarked that stacking incentives can be difficult. Each incentive program has a separate application process with different timelines that may disburse funds at different stages of the project. Funding timelines misaligned with project needs can create cash flow problems. Incentive programs can also come with requirements, such as the use of the resulting infrastructure. For instance, the Joint Utilities of New York provide 90% of the cost of make-ready equipment if it is publicly available but 50% if it is for restricted or private use (Joint Utilities of New York, 2023). Moreover, when a project includes the deployment of electric vehicles and the accompanying infrastructure, vehicle funding may not match infrastructure funding. For example, a project may receive funding for ten vehicles but for only five charging stations.

Rural communities may struggle to support charging infrastructure

The efforts to install tens of megawatts of transmission and distribution capacity required in certain counties for MHDV charging differ between urban and rural settings. While urban areas are typically served by large investor-owned utilities, rural locations are typically served by member-owned electric cooperatives. One interviewee indicated that such cooperatives often do not have the in-house design and engineering staffing capabilities required to support charging infrastructure deployment. To make up for a lack of resources, they are required to hire an external engineering firm and incur additional costs.

In rural settings, the most common commercial fleets suitable for electrification are school bus fleets belonging to local school districts. Fleet uniformity and short, predictable routes make bus electrification a key target among utilities and regulators. However, an interviewee representing rural utilities indicated that rural school districts are systematically underfunded and do not feel well-positioned to take on electric school bus pilots.

Opinions about project bottlenecks vary

Conversations with different stakeholders revealed varied opinions regarding the major bottlenecks to charging infrastructure deployment. Utility representatives and one port representative remarked that the current grid infrastructure is capable of handling initial deployments of vehicles and chargers. Where grid capacity runs short, they discussed options such as managed and off-peak charging that can serve fleets while more capacity is installed. These interviewees expressed that their projects are often delayed by slow vehicle delivery timelines, many of which were exacerbated by pandemic-related supply chain delays. Another bottleneck cited was the lack of information about how much capacity is required and where it should be located.

Others pointed to the difficulties in getting equipment into the ground. One interviewee noted that transformers can take 3 years to order, manufacture, and install, delaying necessary service upgrades to serve heavy-duty fleets. Another expressed concern about the misalignment between infrastructure projects and equipment stock: equipment manufacturers may not keep equipment stocked for whenever project developers win grants and contracts.

Differing opinions on project bottlenecks indicate both the complexity of installing charging infrastructure and the abundance of opportunities at all stages of project development and deployment to improve the process and to achieve a single completion date for all involved parties.

OPTIONS FOR ENABLING CHARGING INFRASTRUCTURE DEPLOYMENT

The options presented below address the challenges identified and have the potential to accelerate charging infrastructure deployment. These options were developed with information derived from literature on grid infrastructure and discussions with stakeholder interviewees and advisors to the ICCT.

In this section, charging infrastructure generally refers both to grid assets, including distribution substations and feeders, as well as chargers and related equipment at depots and public charging hubs. Most options focus on the grid infrastructure, which was identified to present the most challenges. While the identified options operate on different timeframes, there is an opportunity to begin implementation immediately. Therefore, the options below are organized by the level of administrative, regulatory, or legislative change and complexity required by each option. The options listed are illustrative examples and do not cover the full suite of actions that can be initiated to enable the buildout of MHDV charging infrastructure. Our discussion is intended to illustrate the breadth of opportunities to accelerate the adoption of zero-emission MHDVs.

Options that do not require regulatory approval

Many of the options below to enable MHDV electrification are typically within the control of a single actor, such as a fleet, utility, or local jurisdiction, and may require the actor to change internal policies and procedures. These options work with what is already possible within the existing regulatory framework and are achievable in the 2023–2027 timeframe.

Utilities

Short-term load rebalancing. Utilities can evaluate current loads and identify headroom capacity that could be created by shifting loads between neighboring feeders, either seasonally or for longer durations. Load rebalancing can optimize the use of existing distribution infrastructure to accommodate new MHDV charging loads while maintaining overall system reliability for customers. Once permanent grid capacity is added, feeders can be returned to the prior grid network arrangement.

Use non-firm distribution capacity. Utility planners typically set substation and feeder loading limits that represent worst-case scenarios such as full charger utilization during peak demand, or infrequent, “1-in-10”[2] events (Keen et al., 2022; Carden, Wintermantel, & Pfeifenberger, 2011). Planners also account for the effects of weather conditions on the load-carrying capabilities of distribution assets. Since high load and adverse weather conditions are rare occurrences, some grid capacity is available on a flexible basis to charge MHDVs. Depot charging typically occurs at night when feeder loads are lower and cooler temperatures at night can maximize line capacity.

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[2] Depending on the utility, this may be defined as one load shedding event or one day of load shedding every 10 years. Load shedding occurs when power demanded by grid users outstrips available capacity, and certain loads must be “shed” to match supply with demand.

Incorporate smart charging into feeder ratings and load forecasting. It is common for utilities to calculate available capacity based on annual peak load, regardless of season or time of day. Depot charging is well-suited for charge management through built-in vehicle software or fleet management software. Utility planners can base capacity on load profiles that account for smart charging and are thus more accurate on seasonal and daily time scales; these load profiles can be included in customer service contracts to create more certain load forecasts.

Enable third-party funding, design, and construction. To address a lack of staffing and financial resources, utilities can partner with third parties for the design, construction, and funding of grid upgrades. In a recent example, Tesla provided design and engineering services for chargers in two PepsiCo locations (CNBC, 2022). One anonymous vehicle manufacturer representative expressed interest in paying for grid upgrades to facilitate the adoption of ZEVs. While investor-owned utilities may view this arrangement as a lost opportunity to increase their rate base and provide returns for investors, public utilities and rural electric cooperatives following alternate rate structures may be more amenable to external funding and construction.

Local and state agencies

Expedite and streamline review and permitting. The installation of charging infrastructure is often met with delays due to plan reviews, permitting, and inspection required by local jurisdictions. The average time to complete the permitting process for a DC fast charging station site is 65 days across the U.S., while in California the average is 81 days (Electrify America, 2022). Permitting processes also differ between jurisdictions, creating an additional challenge for utilities and fleets spanning multiple areas. To streamline charger permits, California has enacted Assembly Bill 1236, directing jurisdictions to enact a streamlining ordinance (Local Ordinances: Electric Vehicle Charging Stations, 2015). The California Governor's Office of Economic and Business Development has also created a permit streamlining guidebook that includes sample ordinances (Hickerson & Goldsmith, 2023). Moreover, jurisdictions can offer clear timelines on when permits can be expected and when inspections can be completed.

Coordinate the availability of incentives with vehicle delivery and charging infrastructure deployment timelines. A project proponent, such as a fleet, can take advantage of several incentives available from state, regional, and local governments, and utilities. However, incentive programs administered by separate entities often do not have similar application deadlines or incentive voucher validity dates. In addition, the time needed for grid capacity additions or truck delivery time is often not considered. Misalignments in incentive stacking can be reduced with improved incentive pairing, where incentive availability is coordinated with vehicle delivery and infrastructure deployment timelines.

Fleets and utilities

Collaborate with electric vehicle manufacturers to submit grid connection applications. Fleets and electric MHDV manufacturers can collaborate on submitting multi-year grid connection applications early to local electric utilities, thus providing utilities with the empirical evidence they require to affirm the likelihood of charging loads. Fleets can establish manufacturers as third-party proxies to apply on their behalf, provided they have legal staff to do so. Meanwhile, utilities can make greater use of existing third-party application processes, and fleets should proactively engage their legal departments in establishing third-party proxies to apply on their behalf.

Options that require administrative consent or regulatory approval

The possible actions listed below are strategic and planning-oriented options that may require regulatory approval, or at the very least, administrative consent.

Utilities and regulatory bodies

Modify programs as market conditions change. Utility regulators can consider periodic adjustments to transportation electrification programs to better respond to fleet market changes and meet program goals. These programs, which include the installation of make-ready infrastructure and charging ports, are typically approved on a case-by-case basis with well-defined scope and duration of 3–5 years. This approach lacks the flexibility required to meet rapidly evolving market conditions and may have the adverse effect of delaying the transition to zero-emission MHDV transportation.

Explicitly incorporate transportation electrification load forecasts into distribution system planning and grid capacity investments. Unlike buildings, vehicles are mobile loads that can shift on short time scales. Incorporating fleet data into utility load forecasting tools is imperative, and regular updating is required to reflect changes in fleet operations. Because MHDV charging loads will concentrate in certain locations in a utility's service area, a close examination of the readiness of existing distribution systems is also required. With this information, utilities can develop specific capacity addition project plans for approval to deploy infrastructure in time to meet fleets' plans to switch to electric MHDVs.

Utilities and regulators can also examine rate designs and structures to reduce the impact of traditional demand charges during early charging sessions, choosing to recover their costs through a more volumetric approach to electricity pricing.

Fleet operators, property owners, and utilities

Align electrification responsibilities and timelines for leased properties. Proposed regulations place the primary responsibility on fleets to electrify vehicles. As discussed in previous options, fleets must also make transportation electrification requests to utilities and serve as the customer of record. However, fleets often operate from leased facilities, and property improvements to enable vehicle electrification, such as cabling, switchgears, or transformers, must be approved by land and building owners. For fleets to receive utility program benefits, such as grants covering make-ready costs, they are often required by utilities to secure property owner approval and commit to use power at that location for an extended period of 5–10 years. Meanwhile, fleets may have much shorter lease terms with landlords. The current model involves a challenging mismatch between fleet operators and property owners regarding the responsibility to electrify, the ability to make changes on to properties, and the length of power use commitments.

Realignment of these interests to focus on an agreement between property owners and utilities will remove a considerable barrier to this transition to MHDV electrification, as many fleets operate their businesses from leased facilities. For example, programs can provide incentive funds to property owners who lease their land to prospective electric MHDV operators. The on-site charging infrastructure can then be considered an amenity for the tenant that can pay for those costs through property lease payments.

Options that require regulatory approval or enabling legislation

The options described below that require regulatory approval or legislation will be needed to reach electrification and decarbonization goals. Because of the time required to complete these actions, efforts to enact such polices should begin immediately.

Utilities, regulators, and legislators

Increase role clarity. Despite near-uniform agreement that the utilities will play an important role in deploying grid infrastructure to support transportation electrification, many states have not clearly defined or enshrined this role in legislation. Where needed, state legislatures are encouraged to pass appropriate legislation to clearly define the role of electric utilities and regulators in transportation electrification. Legislation and regulation to date have focused primarily on the role of utilities in owning, deploying, and operating charging stations. Since there is much disagreement on the role of utilities in charging station deployment, these efforts have seen mixed success. However, grid infrastructure investment is critically needed for MDHV fleet electrification.

"Pre-build" authorization of grid transmission and distribution infrastructure in "no regrets" zones that align with vehicle manufacturer and fleet compliance requirements. With legislative approval, regulators can authorize utilities to invest in grid capacity additions in designated zones where electric MHDVs are highly likely to congregate, based on regulatory compliance requirements placed by states on manufacturers and fleets such as the ACT rule. California Assembly Bill 2700 takes a first step in this direction, calling for California utilities to incorporate fleet data to ensure the distribution grid is ready for MHDV charging (Transportation Electrification: Electrical Distribution Grid Upgrades, 2022). However, this legislation does not appear to enable grid capacity buildouts in anticipation of fleet electrification.

Shift MHDV charging loads to higher-voltage parts of the grid. Other options at the regulatory level include allowing and encouraging connections to transmission lines along highways. A proposed bill in New York would establish a highway charging plan and streamline the installation of infrastructure along state freeways, as well as identify high-priority areas for the deployment of MHDV charging infrastructure. Others have also recommended installing chargers in close proximity to high power lines along highways (National Grid, 2022).

CONCLUSIONS

Building the charging and refueling infrastructure required to support an accelerated transition to zero-emission MHDVs requires timely investments and policy support. A full network of charging infrastructure covering the entire United States is not needed in the near term. To best manage resources, infrastructure deployment in the near term should be prioritized in areas that are expected to see the highest energy needs from MHDV traffic flows in 2025 and 2030. Industrial areas in the largest metropolitan areas—including Boston, Chicago, Dallas, Houston, Los Angeles, New York, and Phoenix—are expected to require most of the charging needs in the near term, driven first by the energy needs of short- and regional-haul trucks and buses. California and Texas are standout priorities, accounting for a combined 19% of the projected nationwide charging needs in 2030. Seven of the top ten counties by absolute charging needs in 2030 will be in these two states.

As the zero-emission-MHDV market develops, charging needs are expected to expand along freight corridors that connect those industrial nodes. Deploying charging infrastructure along NHFN corridors can accommodate up to 85% of the charging needs from long-haul trucks by 2030. Those charging needs can be satisfied by setting traffic-based targets for the deployment of charging stations every 50 miles, in line with FHWA's AFCs, as well as introducing additional criteria for MHDV compatibility, including pull-through lanes, and wide ingress and egress requirements.

Projections of the total energy consumption of the electric MHDV fleet in 2030 represent less than 1% of the national electricity retail market in 2021, suggesting that MHDV electrification will not be limited by electric power generation capacity. However, peak charging loads of up to 132 MW are expected in identified priority counties by 2030, requiring timely planning and construction to ensure transmission and distribution systems can accommodate the needs of MHDV electrification. There are immediately actionable options to optimize the use of existing grid capacity, including smart charging, load rebalancing, and making use of non-firm capacity. In parallel, modifications to existing policy frameworks are needed to enable utilities to incorporate projections of future charging load when planning for near- and long-term grid capacity building.

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APPENDIX

ZERO-EMISSION MHDV STOCK PROJECTIONS

Table A1. Zero-emission MHDV stock projections through 2030 based on potential ZEV market growth

MHDV segment	2023 total stock[1]	2023 sales share	2023	2024	2025	2026	2027	2028	2029	2030
Combination long-haul truck	1,696,626	15%	258	743	1,745	3,639	6,948	12,481	21,345	34,977
Combination short-haul truck	983,872	9%	1,421	4,555	10,643	20,315	34,781	54,759	75,978	98,506
Other buses	342,644	3%	2,753	5,450	9,104	13,619	18,783	24,422	30,264	36,136
Refuse truck	59,319	1%	563	1,174	1,902	2,898	4,267	6,029	8,204	10,789
School bus	529,539	5%	4,525	9,183	15,704	23,396	31,657	40,190	48,849	57,664
Single unit long-haul truck	208,063	2%	2,121	4,710	7,797	11,524	16,044	21,108	27,452	35,164
Single unit short-haul truck	4,760,342	54%	48,111	106,835	176,815	261,384	363,819	478,674	622,466	797,282
Transit bus	145,053	1%	3,094	4,160	5,616	7,468	9,445	11,582	14,186	17,254
Class 4-8 MHDV	**9,370,253**	**100%**	**62,846**	**136,810**	**229,326**	**344,243**	**485,744**	**649,245**	**848,744**	**1,087,772**

Source: Ragon et al. (2023)

[1] *Total vehicle stock including all powertrains*

VEHICLE TECHNICAL CHARACTERISTICS AND ENERGY CONSUMPTION

Table A2. Daily VKT and average energy intensity of each battery-electric MHDV segment

MHDV segment	Mean daily VKT	2030 Battery capacity (kWh)	BEV energy intensity (kWh/km)		
			2023	2030	2040
Combination short-haul truck	432	455	1.42	1.35	1.28
Combination long-haul truck	522	920	1.46	1.35	1.24
Single unit short-haul truck	80	205	0.72	0.70	0.66
Single unit long-haul truck	322	405	0.96	0.92	0.87
Refuse truck	113	205	1.26	1.20	1.14
Transit bus	161	450	0.76	0.74	0.71
School bus	97	180	0.82	0.79	0.75
Other buses	161	670	1.13	1.08	1.03

Source: Slowik et al. (2023)

MHDV CHARGING CHARACTERISTICS

Table A3. Charging characteristics for each MHDV segment in 2030

Vehicle category	Average overnight charging power (kW)	Share of energy from 50–150 kW overnight charging (charger size)	Share of energy from CCS charging (350 kW)	Share of energy from MCS charging (2 MW)
Combination Short-haul Truck	63	77% (150 kW)	6%	17%
Combination Long-haul Truck	127	82% (150 kW)	1%	16%
Single Unit Short-haul Truck	28	96% (100 kW)	4%	<1%
Single Unit Long-haul Truck	56	75% (100 kW)	8%	17%
Refuse Truck	28	96% (50 kW)	2%	2%
Transit Bus	62	100% (100 kW)	0%	0%
School Bus	25	96% (50 kW)	4%	<1%
Other Buses	93	>99% (100 kW)	<1%	<1%

Notes: The average charging power for each segment is defined as the minimum power required to fully recharge the battery within 8 hours. Battery sizes are listed in Table A2. The rated charger power is specified from our understanding of fleet preferences and common practices, based on discussions with industry, and informs our estimates of installed nameplate capacity. In practice, charging will likely occur at a lower power. All fast chargers are rated at 350 kW and all ultrafast chargers at 2 MW. This table was updated on May 22, 2023 to accurately reflect modeling assumptions.

Table A4. Projections on the share of MHDV charging that will occur at private depot and public locations in 2030 for each MHDV segment

Vehicle category	Share of overnight charging		Share of fast charging		Share of ultrafast charging	
	Depot	Public	Depot	Public	Depot	Public
Combination long-haul truck	0%	100%	0%	100%	0%	100%
Combination short-haul truck	0%–50%	50%–100%	0%–50%	50%–100%	0%–50%	50%–100%
Other buses	100%	0%	0%	100%	0%	100%
Refuse truck	100%	0%	100%	0%	100%	0%
School bus	100%	0%	100%	0%	100%	0%
Single unit long-haul truck	0%	100%	0%	100%	0%	100%
Single unit short-haul truck	100%	0%	50%	50%	50%	50%
Transit bus	100%	0%	100%	0%	100%	0%

BREAKDOWN OF HPMS TRAFFIC BY VEHICLE SEGMENT

Table A5 gives the breakdown of single-unit and combination HPMS activity data into MOVES categories, The following road type definitions are used to obtain this breakdown:

- Restricted: FHWA functional class 1 (interstate) or class 2 (other highway/freeway)
- Urban: area designated as urban by FHWA
- Rural: any area not designated as urban by FHWA urban code 99999 or 99998 (small urban area classified as rural)

Table A5. Portion of activity assigned to each vehicle segment by road classification

	Vehicle segment	Rural restricted	Rural unrestricted	Urban restricted	URBAN UNRESTRICTED
Single unit	**Transit bus**	0.04850	0.04346	0.05937	0.05755
	School bus	0.06345	0.06491	0.05554	0.06656
	Refuse truck	0.01248	0.01236	0.01315	0.01192
	Other bus	0.11218	0.09871	0.10914	0.12767
	Single-unit short-haul	0.68282	0.69774	0.68659	0.65609
	Single-unit long-haul	0.04310	0.04695	0.04488	0.04702
	Total	**1.00000**	**1.00000**	**1.00000**	**1.00000**
Combination	**Short-haul**	0.10994	0.24831	0.18784	0.27344
	Long-haul	0.89006	0.75169	0.81216	0.72656
	Total	**1.00000**	**1.00000**	**1.00000**	**1.00000**

STATE-LEVEL ENERGY NEEDS FOR MHDV CHARGING

Table A6. State total daily VKT, projected eVKT, and energy consumption from MHDV charging in 2030

Rank in U.S.	State	Total daily VKT, Class 4-8 MHDVs (km)	Total daily EVKT, Class 4-8 MHDVs (km)	Daily energy consumption from MHDV charging (MWh)	Share of national energy consumption
1	Texas	399,709,982	40,312,189	15,481	11%
2	**California***	180,728,114	23,719,908	11,196	8%
3	Florida	173,896,420	22,567,351	7,318	5%
4	Illinois	175,651,553	21,458,150	5,958	4%
5	Ohio	287,891,326	33,997,112	5,226	4%
6	Pennsylvania	61,592,322	8,415,755	5,035	4%
7	Indiana	216,660,885	27,157,127	4,962	4%
8	Alabama	257,245,597	29,862,818	4,790	3%
9	South Carolina	82,280,671	10,624,152	4,233	3%
10	**New York***	50,770,266	6,923,440	4,231	3%
11	North Carolina	53,891,297	6,437,763	4,218	3%
12	Arizona	51,475,628	4,877,323	3,990	3%
13	Georgia	91,586,750	8,607,761	3,758	3%
14	Utah	47,622,932	6,251,845	3,511	3%
15	Tennessee	118,408,227	12,125,813	3,413	2%
16	Louisiana	98,036,625	7,955,230	3,374	2%
17	Minnesota	51,268,946	5,916,255	2,972	2%
18	Missouri	123,615,392	14,441,444	2,928	2%
19	Wisconsin	37,060,282	4,688,929	2,612	2%
20	Arkansas	106,301,592	9,516,692	2,419	2%
21	Michigan	154,517,473	14,275,865	2,398	2%
22	**Washington***	60,919,508	5,450,202	2,398	2%
23	Kansas	69,728,742	7,412,263	2,349	2%
24	Virginia	28,852,554	2,751,245	2,317	2%
25	**Oregon***	49,076,476	5,367,451	2,229	2%
26	**New Jersey***	43,720,773	6,348,471	2,047	1%
27	Maryland	62,411,477	7,224,262	2,023	1%
28	Mississippi	32,136,181	3,252,040	1,978	1%
29	Oklahoma	26,823,456	3,242,023	1,921	1%
30	Kentucky	15,191,071	1,480,369	1,885	1%
31	**Colorado***	42,265,662	5,098,477	1,849	1%
32	**Massachusetts***	48,185,397	6,862,962	1,732	1%
33	Iowa	28,790,836	2,558,494	1,656	1%
34	Connecticut	23,020,422	3,108,885	1,441	1%
35	New Mexico	17,004,048	1,654,554	1,161	1%
36	West Virginia	17,814,269	1,735,043	1,157	1%
37	Idaho	11,741,013	1,248,862	1,051	1%
38	Wyoming	6,080,472	963,286	946	1%
39	Nevada	58,262,631	7,233,597	853	1%
40	North Dakota	15,052,098	1,454,934	798	1%
41	Maine	11,582,808	1,322,564	748	1%
42	Nebraska	10,109,552	664,584	714	1%
43	Montana	8,680,514	742,373	525	0%
44	Delaware	3,580,528	500,670	500	0%
45	South Dakota	5,895,486	405,707	486	0%
46	New Hampshire	1,768,189	253,721	410	0%
47	Rhode Island	1,866,740	265,646	318	0%
48	**Vermont***	1,909,384	212,349	276	0%
49	District of Columbia	753,610	129,816	75	0%
U.S. total		**3,523,436,176**	**399,077,768**	**139,865**	**100%**

Note: States are ranked in descending order of daily energy consumption.

*States that have adopted the ACT as of April 2023. Other states are in the process of adopting the ACT.

COUNTY-LEVEL CHARGING NEEDS

Rank	County	Daily energy consumption (MWh)	Estimated peak charigng load (MW)	Overnight chargers	Fast chargers	Ultrafast chargers	Nameplate capacity of chargers on local distribution grid (MW)
1	**Los Angeles, CA**	1,791	132	8,666	80	38	974
2	**Maricopa, AZ**	1,616	119	7,125	72	41	832
3	**Harris, TX**	1,613	119	7,036	72	41	826
4	**Cook, IL**	1,266	93	6,051	57	28	683
5	**Dallas, TX**	1,019	75	3,963	45	31	490
6	**San Bernardino, CA**	943	70	4,166	41	23	482
7	**San Diego, CA**	940	69	4,463	42	21	505
8	**Salt Lake, UT**	937	69	5,014	42	16	541
9	**Riverside, CA**	708	52	3,360	31	15	379
10	**Bexar, TX**	698	51	2,789	31	20	340
11	**Tarrant, TX**	665	49	2,645	30	20	324
12	**Orange, CA**	620	46	3,165	28	12	348
13	**Jefferson, AL**	607	45	2,433	27	18	297
14	**Marion, IN**	552	41	2,461	25	14	287
15	**Franklin, OH**	528	39	2,258	24	14	267
16	**King, WA**	503	37	2,344	23	12	267
17	**Pulaski, AR**	499	37	1,473	22	19	208
18	**Broward, FL**	496	37	2,430	22	11	272
19	**Miami-Dade, FL**	495	37	2,495	23	10	276
20	**Utah, UT**	495	37	2,470	23	10	274
21	**Orange, FL**	483	36	2,381	22	10	265
22	**Palm Beach, FL**	475	35	2,310	22	10	259
23	**Kern, CA**	465	34	1,934	20	12	229
24	**DuPage, IL**	442	33	2,207	20	9	245
25	**Hennepin, MN**	437	32	2,127	20	9	238
26	**Alameda, CA**	417	31	1,998	19	9	225
27	**Duval, FL**	417	31	1,954	19	10	222
28	**Santa Clara, CA**	417	31	2,080	19	9	231
29	**St. Louis, MO**	413	30	1,771	19	11	209
30	**Hillsborough, FL**	408	30	1,969	19	9	221
US total		**139,893**	**10,317**	**580,054**	**7,869**	**5,639**	**69,157**

Note: Counties are ranked in descending order of energy consumption. This table was updated on May 22, 2023 to accurately reflect modeling assumptions.

Table A8. Top 1% of U.S. counties with the highest energy consumption from MHDV charging per unit area

Rank	County	Energy consumption per unit area (kWh/m²)
1	Bronx, NY	1,579
2	New York, NY	1,308
3	Queens, NY	982
4	Kings, NY	854
5	Suffolk, MA	700
6	Richmond, NY	651
7	Philadelphia, PA	571
8	Hudson, NJ	549
9	Marion, IN	535
10	**Cook, IL***	513
11	DuPage, IL	510
12	San Francisco, CA	509
13	District of Columbia	456
14	Salt Lake, UT	454
15	Fredericksburg, VA	454
16	Denver, CO	447
17	Milwaukee, WI	442
18	Union, NJ	437
19	**Dallas, TX***	433
20	Essex, NJ	417
21	Bristol, VA	409
22	Franklin, OH	377
23	Ramsey, MN	373
24	**Harris, TX***	349
25	Harrisonburg, VA	349
26	Hamilton, OH	327
27	Middlesex, NJ	323
28	Bergen, NJ	312
29	**Orange, CA***	301
30	**Tarrant, TX***	287
U.S. average		**29**

*Also ranks in the top 1% for counties with the highest absolute energy consumption.