Working Paper

Phasing in U.S. Charging Infrastructure

An Assessment of Zero-Emission Commercial Vehicle Energy Needs and Deployment Scenarios

Michael Joseph
Bill Van Amburg
Mark Hill
Bharadwaj Sathiamoorthy

August 2023

CALSTART

Acknowledgments

The authors would like to thank key CALSTART staff, including Chase LeCroy, Jessie Lund, and Jasna Tomić, for their critical review of and additions to this report. Any errors are the authors' own.

CALSTART

www.CALSTART.org

@CALSTART

Table of Contents

List of Acronyms

Acronym	Definition
ACF	Advanced Clean Fleets rule
ACT	Advanced Clean Trucks rule
bhp-hr/mile	Brake horsepower-hour per mile
CaaS	Charging-as-a-Service
CARB	California Air Resources Board
CEC	California Energy Commission
CPUC	California Public Utilities Commission
EPA	U.S. Environmental Protection Agency
EVSE	Electric vehicle supply equipment
FHWA	Federal Highway Administration
Global MOU	Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles
HPMS	U.S. Highway Performance Management System
ICCT	International Council on Clean Transportation
kW	Kilowatts
MHDV	Medium- and heavy-duty vehicle
MWh	Megawatt-hours
NEVI	National Electric Vehicle Infrastructure Formula Program
NHFN	National Highway Freight Network
NREL	National Renewable Energy Laboratory
PNNL	Pacific Northwest National Laboratory
SCAQMD	South Coast Air Quality Management District
VMT	Vehicle miles traveled
ZE-MHDV	Zero-emission medium- and heavy-duty vehicle

Figures and Tables

Figures

Tables

Executive Summary

To assess the feasibility of zero-emission infrastructure buildout at a nationwide scale, CALSTART projected the infrastructure required to supply the electricity needed for zero-emission medium- and heavy-duty vehicle (ZE-MHDV) adoption rates in 2027, 2030, and 2035. These rates meet the targets set by the Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles (Global MOU), signed by the United States in 2022.

This analysis shows that the infrastructure necessary to meet energy needs of ZE-MHDVs can be **phased in** around favorable launch areas. This phased approach can manage distribution grid upgrade timelines and maximize utilization even with the Global MOU's attainable market penetration rates, which exceed those proposed by U.S. regulators. **The accelerating pace of ZE-MHDV energy needs can be managed through market-driven, overlapping, and concurrent growth of an integrated transportation-energy system**.

To develop this analysis and resulting roadmap, CALSTART modeled energy needs and showed how prioritizing favorable launch areas and using innovative deployment strategies can accommodate capacity constraints during buildout. Favorable regions include where 1) industry concentrates, 2) public and private funds have high leverage, 3) policy is supportive, 4) energy will cost less, or 5) distributed grid modernization will occur. Buildout in this scenario concentrates first around return-to-base depot infrastructure in key industry clusters that form recharging hubs, then in key corridors enabling regional hub-to-hub operations, and finally in national network nodes.

In sum, this **phase-in strategy** enables:

- **Faster deployment by focusing on priority launch areas.** More ZE-MHDVs can be supported in less time than in linear, unphased growth scenarios.
- **Cost-effective implementation.** Costs can be shifted forward and less important areas left to future deployment, while total energy demand can be supplied through targeted upgrades and management strategies, sharing arrangements, public charging, and other onsite optimizations—reducing per-vehicle infrastructure costs.
- **A clear vision that helps utilities, government, and investors target actions** to integrate grid modernization and ZE-MHDV adoption, as well as maximize co-benefits.
- **Coordination that leverages public funds and unleashes private investment**.

I. Infrastructure Buildout to 2035

Introduction

The development of widely available recharging infrastructure for zero-emission medium- and heavy-duty vehicles (ZE-MHDVs) is critical to support the transition to these vehicles expected in the United States over the next decades. ZE-MHDVs are ready to expand into all regional applications and longer-range routes. Deploying energy delivery systems—a package of technology products and supportive system developments making up a *recharging infrastructure* that supports the introduction of ZE-MHDVs—is crucial. Infrastructure deployments must keep pace with the rapid growth of ZE-MHDVs or risk slowing the acceleration of the market.

Over the last few years, industry has made major commitments to build out this infrastructure. Moreover, a growing ecosystem of infrastructure suppliers and solutions are in place to support these investments and manage this transition. Nevertheless, a particular fleet's choice to transition to ZE-MHDVs can be influenced by uncertainty over the availability of recharging infrastructure. Exposure to potential unforeseen costs involved in infrastructure deployment could affect and divert a fleet's pathway toward transitioning to ZE-MHDVs, despite potential advantages regarding total cost of ownership. This concern is particularly acute with respect to electric recharging infrastructure; the delivery of electrons is different from the liquid or gaseous refueling systems fleets may be used to and involves questions regarding the pace of transportation electrification and integration into the larger electric grid.[1]

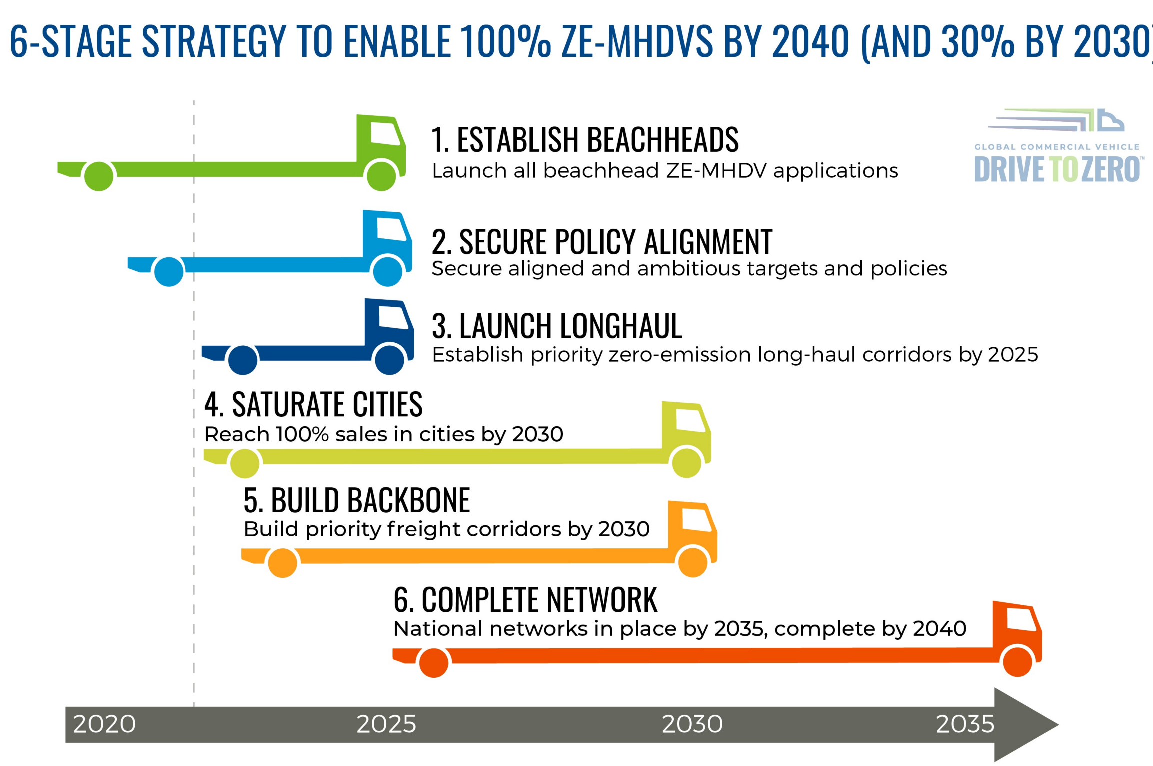
To assess the feasibility of infrastructure buildout at a national scale, CALSTART projected the infrastructure necessary to deliver the electricity needed to meet the ZE-MHDV adoption rates in 2027, 2030, and 2035 set by the Global Memorandum of Understanding on Zero-Emission Medium- and Heavy-Duty Vehicles (Global MOU); these rates represent a feasible pathway to 100 percent ZE-MHDVs by 2040 (CALSTART, 2022b). CALSTART

[1] This analysis focuses on electric infrastructure and leaves the deployment of other zero-emission refueling infrastructure for future studies; recent work has, however, considered the role of other refueling technologies within some of the duty cycles involved in these projections (CALSTART, 2023a).

developed a scenario in which these needs emerge based on current vehicle activity patterns and ZE-MHDV adoption trends. In keeping with CALSTART's overall strategy toward market acceleration and transformation, it was assumed that most of this investment will be through private entities, utilizing innovative strategies many CALSTART members have shared in public discussion on the topic (CALSTART, 2022a; CALSTART, 2022c).

This projection shows how the accelerating pace of ZE-MHDV energy needs can be managed through market-driven, overlapping, and concurrent growth of a supportive ZE-MHDV ecosystem in a **phased** transition. Deployment concentrates first around return-to-base depot infrastructure and in regional recharging hubs within key geographies supporting the full range of regional operations, then in key corridors enabling regional hub-to-hub operations, and finally in built-out networks connecting corridors to each other and to other critical infrastructure along the larger surface transportation network. This assessment was structured to build on and further detail the Drive to Zero implementation roadmap (CALSTART, 2022b). The 2040 ZE-MHDV roadmap's core strategy (Figure 1) breaks up the activity needed to reach full sales penetration into six overlapping stages, with smart infrastructure phasing as a critical, enabling component of five of the stages.

Figure 1. Drive to Zero Six-Stage Strategy (CALSTART, 2022b)



With the **who** and **what** of the ZE-MHDV transition—who is investing in it and the pathway they are on to 100 percent ZE-MHDVs—already known, this study analyzes **where** ZE-MHDVs are likely to appear, **why** they appear in those locations, **when** they will need infrastructure, and **how** this phased buildout process will accommodate them. This first section presents this projection, detailing the scale and pace of the transition in terms of energy delivery needs and the phases to meet those needs.

Energy Needs of the U.S. ZE-MHDV Transition

ZE-MHDV Adoption Rates

To determine *where* ZE-MHDVs will appear, this analysis used projected commercial vehicle ZE-MHDV market sales from the Drive to Zero zero-emission vehicle market assessment (CALSTART, 2021a). The sales estimations are based on a multifactor forecast, which includes technology readiness and viability for key MHDV duty cycles, total cost of ownership, and production scalability inputs for the primary commercial vehicle categories.

The adoption rates represent the 2040 goal of the Global MOU. Global MOU signatories have pledged to reach 100 percent new ZE-MHDV sales by 2040 and 30 percent new ZE-MHDV sales by 2030; the United States became a signatory in 2022. The Global MOU, co-led by the Government of The Netherlands and Drive to Zero, also aligns with the Paris Agreement to reach net-zero by the middle of the 21st century and to drastically cut emissions to keep the rise in mean global temperature below 2.0 degrees Celsius and limited as far as possible to 1.5 degrees Celsius. This standard is aligned with the targets announced by most major global original equipment manufacturers who have set 2040 as the date by when all new vehicle sales will be zero-emission or fossil-free (CALSTART, 2021a).

The Global MOU adoption rates assume this transition will occur through a phased "beachhead" strategy with respect to market acceleration and technology adoption. In the beachhead strategy, first-mover technology applications like transit buses, cargo vans, and school buses dominate markets. From there, supportive services and a supply chain develops behind these early applications (CALSTART, 2022c).

The ZE-MHDV sales rates assumed in this analysis constitute a share of the total commercial vehicle population, which is significantly higher than those proposed by certain regulatory targets. This includes the U.S. Environmental Protection Agency's (EPA's) recently proposed Phase 3 ruling targets for MHDVs, as well as the Advanced Clean Trucks (ACT) rule of the California Air Resources Board (CARB)—already adopted by several states—and the Advanced Clean Fleets (ACF) rule. These rates also align with other forward-looking rates of adoption used in infrastructure assessments such as those from the International Council on Clean Transportation (ICCT) (ICCT, 2023).

Where and How Energy Needs Will Arise

Using these rates, energy needs and where they will appear were projected by considering how new ZE-MHDV sales, and the infrastructure to support them, would be distributed across the United States. The purpose of this projection was to show that these needs arise from the travel patterns on the existing transportation network used by commercial vehicles. In other words, while individual fleet transitions will collectively add up to a total energy need, they will do this within a travel market with spatially differentiated and regional variations. To demonstrate this, new sales were distributed in relation to vehicle miles traveled (VMT) by commercial vehicles (Classes 3–8) on relevant segments of the ZE-MHDV road network, which was defined as the National Highway Freight Network (NHFN) within the lower 48 U.S. states.[2]

Using Federal Highway Administration (FHWA) Highway Performance Management System data, commercial vehicle activity was calculated on individual road segments and then aggregated into uniform 10-square-mile travel areas (i.e., an analytic grid) across the network. VMT for travel on individual road segments was then calculated within these areas, which was used as a basis for determining new ZE-MHDV introductions by way of a scaling factor. The energy used by travel through an area vis-à-vis all travel on NHFN was related to the energy of potentially introduced ZE-MHDVs in that area to the total ZE-MHDVs forecasted by the Global MOU scenario, given their energy usage, typical range, and other factors. The assumption behind this approach, one of several possible currently being explored, was that the energy used to travel through each area on NHFN will be supplied in similar proportions by a share of newly introduced ZE-MHDVs in the future.[3] More detailed information on the methodology is available in the Appendix.

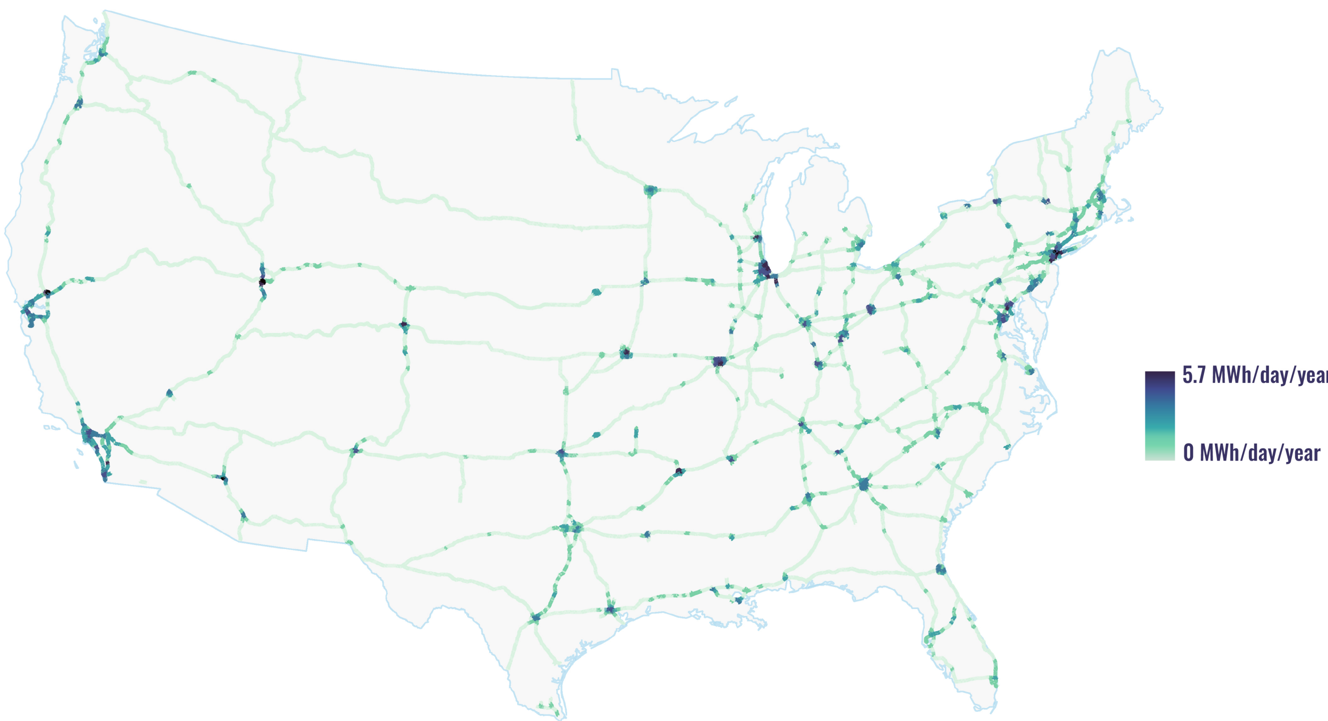
---

[2] NHFN was used given inter-regional and inter-state commercial vehicle travel utilizes much of the freight network. Other states and territories were excluded at this time to focus on the deployment scenarios involving the majority of this network.

[3] This analysis assumes vehicle range and travel patterns are constant through the duration of the projection. There are indicators that these may shift and become more efficient with vocational specialization among ZE-MHDVs.

The introduction of ZE-MHDVs across the road network then presents a consequential change in energy delivery needed to support these vehicles, both in space and over time (Figure 2).

Figure 2. Average Annual Increase in Daily Energy Consumption from New ZE-MHDV Sales, 2023-2035

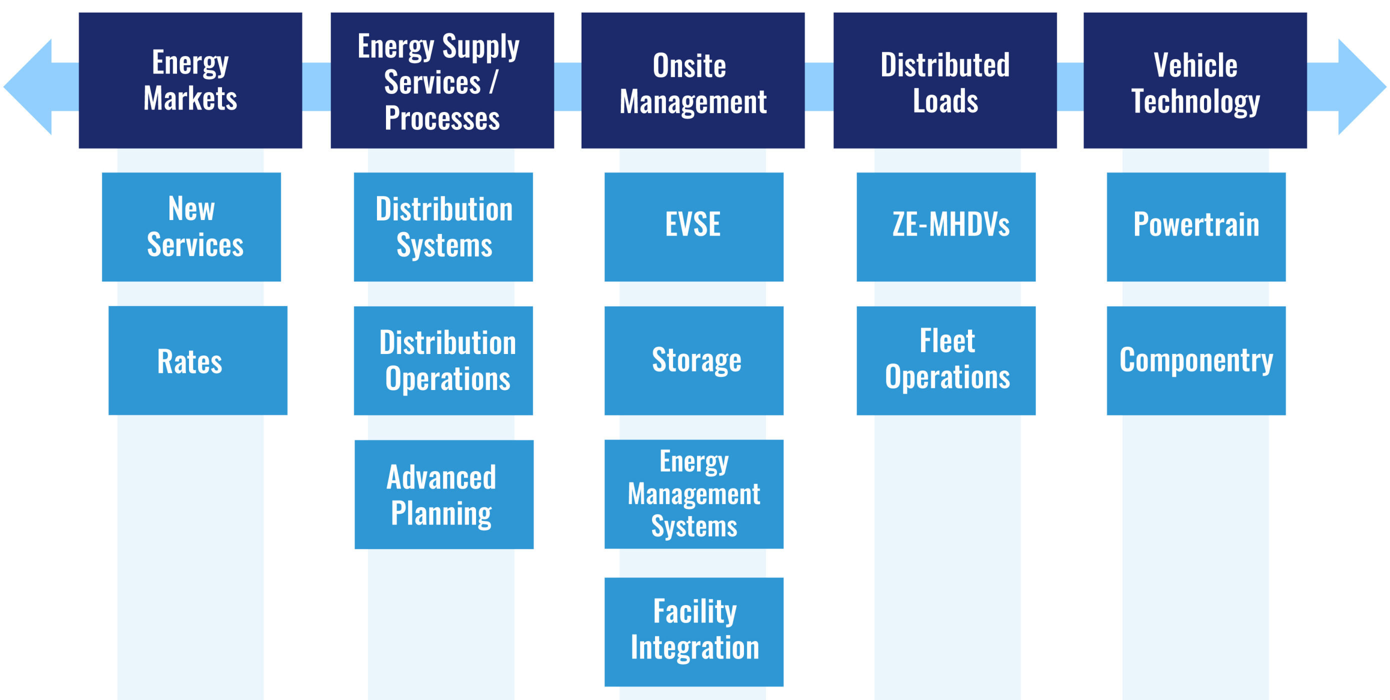


Interpreting these needs correctly is critical for understanding the energy transition and the feasibility of accommodating ZE-MHDVs. First, the spatial variation in energy needs is clearly significant. Needs cluster in areas with high VMT, which include 1) major commercial vehicle centers (including cities but also areas experiencing major industry land uses, like warehousing) and 2) major freight corridors, but also 3) areas where commercial vehicle travel in general is nationally very high. Only after acknowledging this fact can needs represent a total growth in energy demand. Notably, this analysis shows that needs from new deployments are of a magnitude similar to that established in other studies, when adjusting for the more aggressive ZE-MHDV penetration rates of the Global MOU (ICCT, 2023).

Next, there is the change in the amount of energy needed over time. This analysis shows that total electrification needs necessitate a change in the overall energy system to deliver enough energy and manage enough volume to support the consumption of hundreds of thousands of additional megawatt-hours (MWh) per day. Figure 2 above expresses this in terms of an annual rate of change in the daily consumption of energy along the transportation system. In some areas, the average annual increase in daily energy consumption over the timeline of this analysis ranges from increases of up to 0.3 MWh per day to, at the high end, 5.5 MWh per day in certain areas. In some areas, energy systems will need management strategies and upgrades year after year to address a significant change.

Finally, it is important to note that this change in energy needs ultimately represents a change in an energy system. Following both industry and research advances in this area, this study does not approach the necessary change in energy as a simple need for additional capacity—at the same rate, year over year—on the existing system. This analysis underscores that consumption of energy by vehicles constitutes a suite of needs, which can be met in various ways. An optimized ZE-MHDV energy system that finds solutions in several optimization areas will be crucial (Figure 3).

Figure 3. Energy System Optimization Areas



Solutions can be found across each of the axes above to meet the new demand increases across the transportation network. Broad changes at scale in the market itself can form a solution; so, too, can wider grid modernization efforts, including both transmission and distribution system planning and operation improvements to include advance short-term and long-term grid upgrades and the accelerated support for integration of smart energy management technologies, platforms, and services in advance of requests for their deployment (U.S. Department of Energy, 2020). Optimization can also occur by deploying these energy management technologies on or near sites through its configuration. Then, the vehicles (as loads) can be managed through smarter operations, and the actual componentry and vehicle technology can change. Each axis in Figure 3 is a resource for composing solutions to net demand increase issues.

Recent studies on the distribution system generally concur that these upgrades can be made cost effectively and for a fraction of utility investment generally (E3, 2021). They also show that investment in one area may in fact enable, supplement, or substitute investments in others. Increased ability to manage consumption of more MWh is needed, but investments in storage, for example, may ultimately prove a solution in some contexts. In general, this assessment was framed in such a way to make room for multiple development areas in order to cope with energy demand and spur overall energy system modernization.

For the purposes of analysis, the scope of system investments was limited to the deployment of electric vehicle supply equipment (EVSE) necessary to support energy demand, including chargers, make-ready improvements, and storage systems (i.e., onsite storage). Significant distribution system upgrades, onsite generation, and many of the energy system services and other elements in Figure 3 were excluded, but site management and even operational considerations were taken into account for the management of ZE-MHDVs as distributed and variable loads. See the Appendix for more detail on these assumptions.

Where Infrastructure Deployment Will Need to Meet Demand

Next, CALSTART projected the deployment over time necessary to respond to these needs.[4] The detail of the methodology is discussed further in the Appendix.

The analysis considered two options for projections:

- First, the *maximum* number of deployments and their power rating to satisfy energy demand caused by the introduction of a new ZE-MHDV in an area.
- Next, an *optimum* number of energy supply infrastructure to meet new ZE-MHDV introduction over time, which constitutes a phased-in investment scenario.

In the **unoptimized projection**, the *most infrastructure possible* to supply the needs for each new vehicle introduced was deployed. Furthermore, deployment was uniform and indifferent to where each new vehicle would be located, as well as to the timing of investment. Redundancies in deployment were not considered in both time and space, and deployment densified in all areas across the travel network at a constant and undifferentiated rate. The location and pace of deployment had the character of an adoption curve; it did not represent the geography of energy needs corresponding to that curve.

In the **optimized projection**, factors were employed to localize the areas where investment could respond to the most important increases in energy needs over the analysis timeline (from the present to 2035), while accounting for the full pace and scale of the energy needs involved across the network.

The first factor included in the optimized scenario was infrastructure **utilization**. Optimal utilization can achieve a lower levelized cost of infrastructure per unit of electricity delivered to vehicles (Phadke et al., 2021; Borlaug et al., 2020). The optimized projection did not assume buildout was one-to-one with the number of vehicles introduced and was based on assumed rates of charger utilization that could deliver energy needed for the total number of ZE-MHDVs as they are introduced.

[4] Exact deployment locations and configurations were not projected onto parcels of land but were assumed to be within the analysis grid, i.e., within areas accessible by NHFN.

The next factor was the general importance or **priority** of the area for deployment. By concentrating deployments in a particular area, deployment can accommodate more of the share of the distribution of demand. In order to establish priority areas, four general types of priorities were considered:

- **Identified investment priority**: An area has already been indicated as a priority for investment by industry or by supportive federal money such as U.S. Department of Energy ZEV Corridor Planning Partnership Grants.
- **Political, social, and equity priorities**: An area has adopted ACT, or has signed on to or supported the Global MOU, and will benefit from investment in terms of air quality.
- **Industry clustering**: There is a concentration of sectoral activity (i.e., fleet location and growth) in MHDV transportation services, such as warehouses, logistics, or other sectors.
- **Potential for energy system improvements and energy cost reduction**: The overall lowering of levelized cost of energy within regions and the growth of distributed energy resources highlight potential areas where grid improvements of the types needed for EVSE installations will be a priority through 2035.

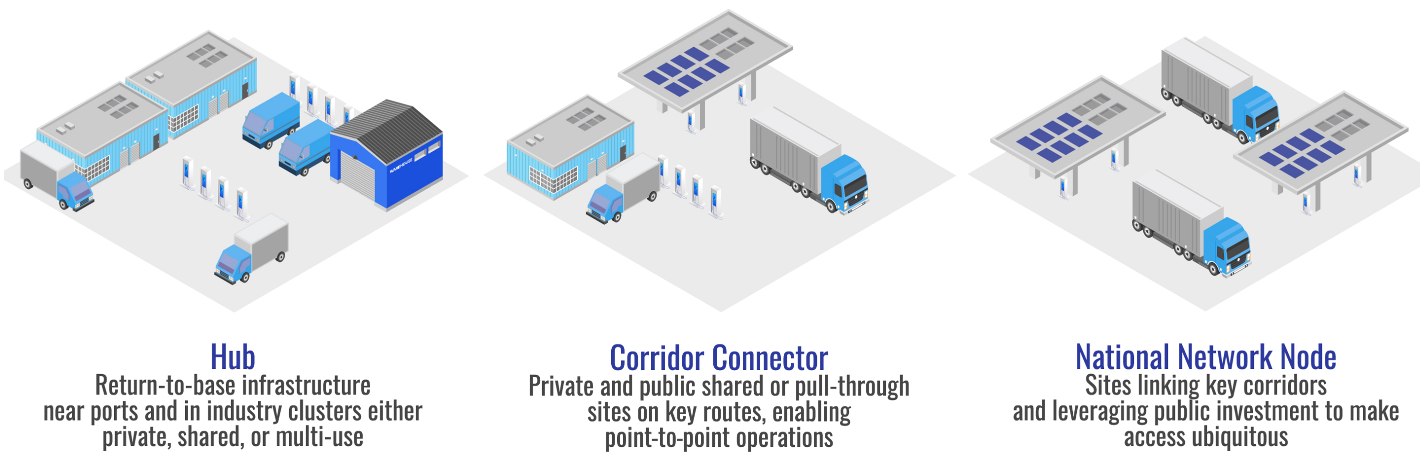
The optimized projection assumed investments will happen across the national network continually throughout the analysis period but are concentrated first in areas that receive high rankings across all of the above priorities. These investment priority factors and utilization efficiencies combine to provide an optimized geography of investment in "priority launch areas," which maximize utilization and investment benefits (Table 1).

Table 1. Priority Launch Area Definitions

Priority Launch Area	Profile	Ranking
Clusters	Concentrated areas of industry activity; where investment, political, social, equity, economic, and energy investments align	Top 33 percent of areas with composite score of priority factors
Corridors	Connectors outside of hubs enabling point-to-point operations	Next highest 50 percent of areas with composite score of priority factors
National Network	Nodes that provide ubiquitous availability, connecting corridors together or linking to national facilities	Next highest 33 percent of areas with composite score of priority factors

Figure 4 illustrates sites and potential site configurations that would be deployed within each launch area corresponding to the descriptions in Table 1 above; it also shows specific duty cycle and vehicle operation considerations enabled by infrastructure buildout within these areas.

Figure 4. Illustration of Site Configurations and Functions in Priority Launch Areas



In this projection, hubs are the highest priority areas, then corridors, and finally areas that constitute a national network, with hubs making up 75 percent of the total deployment, corridors 18 percent, and network nodes 7 percent. It was assumed that some investment will continue within more than one area across the analysis timeline.

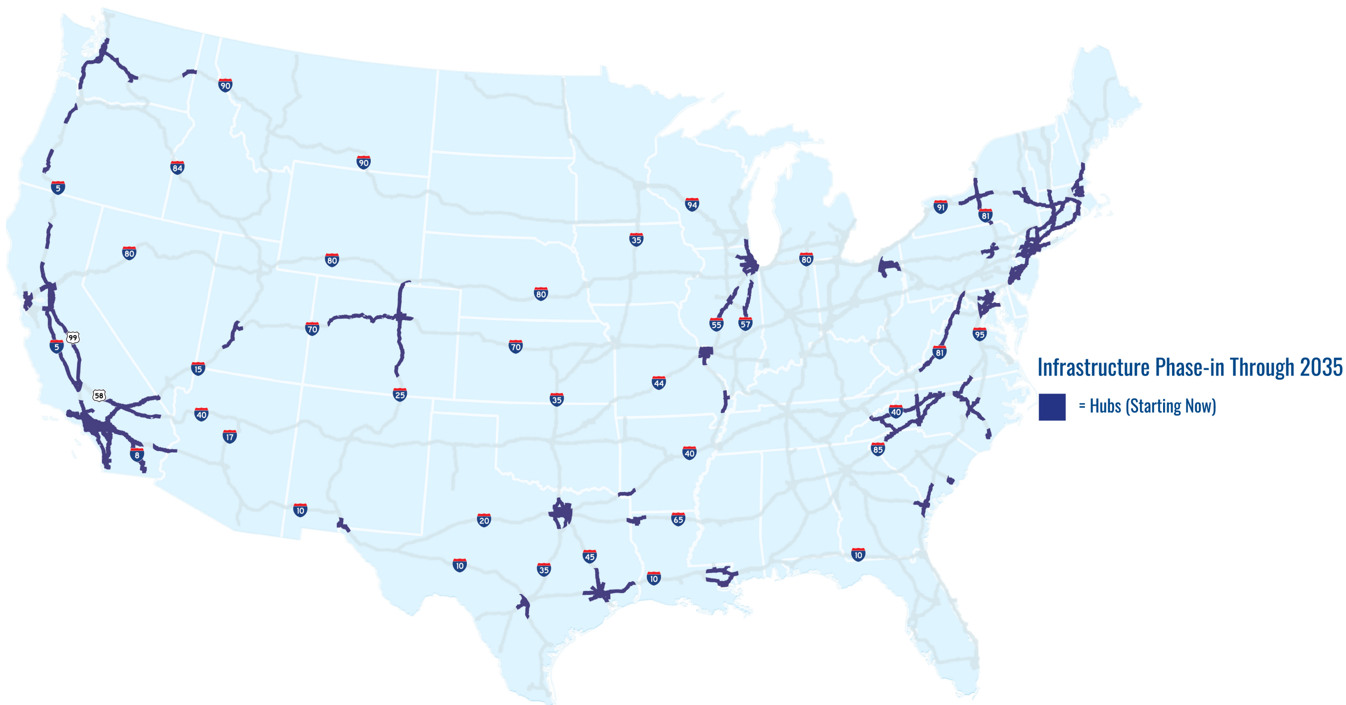
Deployment Phasing

The resulting national roadmap is one in which *phases* of infrastructure investment and deployment accommodate the scale of the ZE-MHDV transition. Below is a description of these results, which will be discussed in more detail throughout the rest of this working paper.

Phase 1 – Major Deployment in Competitive Clusters or Hubs

The first phase (Figure 5) sees investment and market-coordinated activity in and near MHDV-dependent industry clusters, supporting regional freight networks through 2027. This is estimated to be nearly 21 percent of all deployment and would include: 1) about 17 percent of projected infrastructure deployed within major freight industry clusters (composing 24 percent of all hub infrastructure), and 2) about 3 percent of projected infrastructure built on corridors with express industry support or support from federal and state incentive dollars (about 19 percent of all corridor infrastructure). Because investments are located in areas with high priority for overall long-term investment, infrastructure will have a clear relationship with future utilization and overall adoption.

Figure 5. CALSTART Phased Deployment, Present to 2027 – Phase 1



Each phase constitutes all infrastructure needed to support all vehicles as they are introduced over time, which is accomplished at the same adoption rate as an unoptimized scenario. The rate of adoption does not slow in a phased scenario—rather, the opposite occurs. Accordingly, phasing can be expressed as a cumulative share of the total amount of projected infrastructure (i.e., how much that has been built out compared to the total need) and the total number of vehicles supported by this phase (i.e., out of the total number of vehicles full buildout will support) (Table 2).

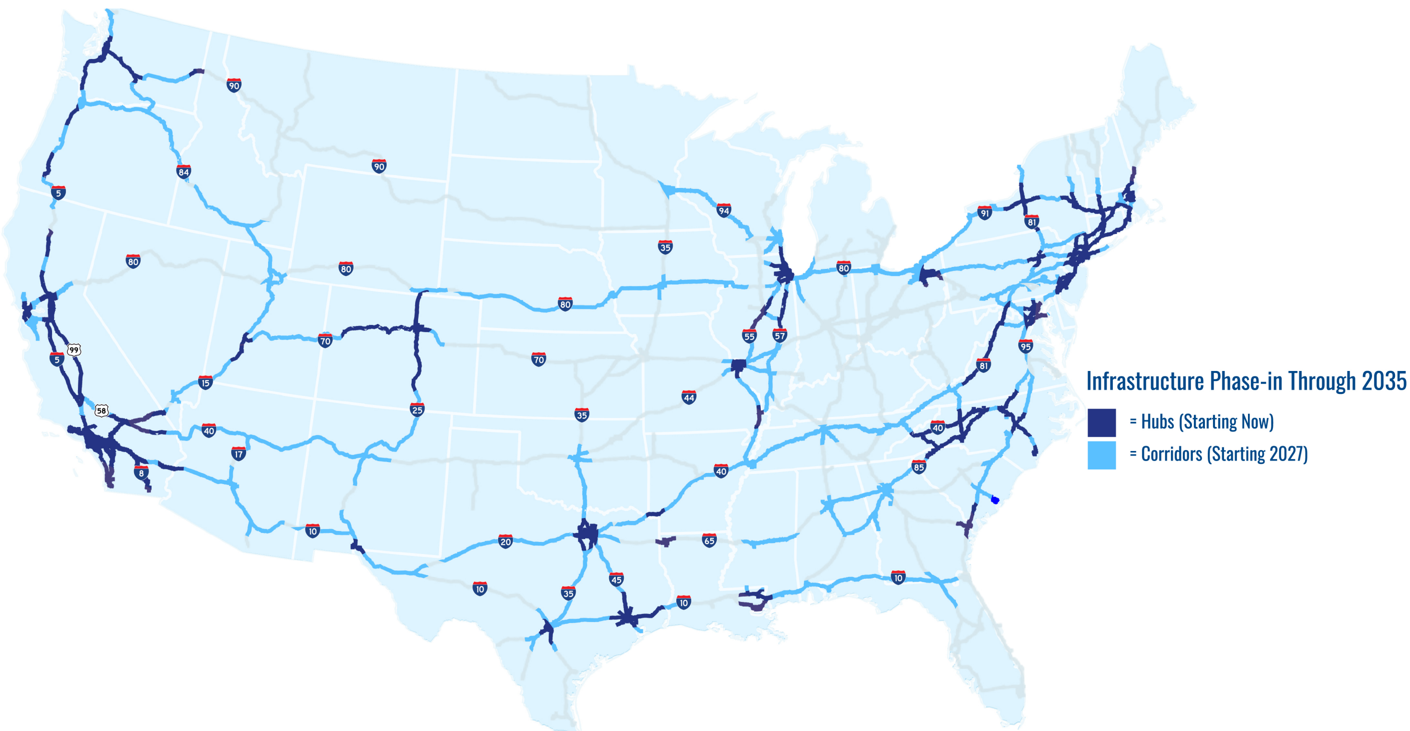
Table 2. Phase 1 Breakdown

Category	Share of Total
Share of Total Infrastructure Deployed in Phase 1	21 percent
Cumulative Share of Vehicles Supported Through Phase 1	16 percent

Phase 2 – Connecting Corridors

The next phase (Figure 6), from 2027 to 2030, will see investments covering 47 percent of total infrastructure needs. These investments center around reinforcing primary hubs, connecting these already identified clusters, and filling out identified corridors.

Figure 6. CALSTART Phased Deployment, 2027 to 2030 – Phase 2



About 53 percent of infrastructure investment in hubs occurs in this phase, the majority (58 percent) of investment in hubs overall (Table 3). At the same time, 9 percent of investment in corridors significantly expands the system, as 46 percent of all corridor development is built out in the Southwest, the Pacific Northwest, the Texas Triangle, and the mid-Atlantic.

Table 3. Phase 2 Breakdown

Category	Share of Total
Share of Total Infrastructure Deployed in Phase 2	53 percent
Cumulative Share of Vehicles Supported Through Phase 2	58 percent

Phase 3 – National Networks

The third phase (Figure 7), from 2030 to 2035, sees continuing investment in hubs and corridors but also in a supportive network for ubiquitous availability of infrastructure, all totaling 26 percent of remaining infrastructure needs (Table 4).

Figure 7. CALSTART Phased Deployment, 2030 to 2035 – Phase 3

Table 4. Phase 3 Breakdown

Category	Factor
Share of Total Infrastructure Deployed in Phase 3	26 percent
Cumulative Share of Vehicles Supported Through Phase 3	100 percent

This phase sees investments making up 3 percent of all total infrastructure in a chain of supportive stops for long-haul trips. Fifty-seven percent of all infrastructure is built in this phase, likely leveraging federal funds, while 7 percent of infrastructure is built out on corridors. The remaining 13 percent of infrastructure continues to be deployed in hubs.

Takeaways

This phase-in scenario meets the ZE-MHDV recharging needs projected in the energy needs analysis. It is, of course, only one possible scenario, but in contrast to other high-level projections, these needs were modeled on plausible considerations of ZE-MHDV market evolution and the recharging infrastructure support required. This analysis was also carried out at a finer resolution than other projections and is consequently able to attend to industry, economic, and other factors that closely integrate deployment with locational and competitive advantages.

The infrastructure deployment necessary to support vehicle adoption no longer appears as an undifferentiated block of investment and energy needs. Instead, it is more like a set of needs that can be approached in steps or chunks and is the outputs of detailed models and simulations that consider actual deployment siting and take into consideration local and regional coordination—such as the California Energy Commission's (CEC's) statewide infrastructure needs assessment, for instance, and also assessments from the National Renewable Energy Laboratory (NREL), the Pacific Northwest National Laboratory (PNNL), the Electric Power Research Institute, and others (CEC, 2021a). In these assessments, some of which CALSTART contributed to or was a project partner on, deployment needs respond to vehicle travel patterns and land uses, as well as the availability of the grid. Rarely does deployment increase across a territory everywhere at once in a straightforward, linear fashion.

In sum, the total phase-in deployment scenario developed differs greatly from a scenario that assumes ZE-MHDV adoption will occur uniformly based on a rate of adoption alone, indifferent to where and how need arises. In an unphased scenario, needs would have to be met identically everywhere at once. Potentially underutilized infrastructure would meet continually increasing energy needs in an unmanaged manner, which has the potential to mischaracterize the challenge of the transition and the nature of ZE-MHDVs; with respect to the distribution grid, both "represent a significant new load and a substantial new source of flexibility" (Pacific Northwest National Lab, 2022).

Figure 8 considers the percentage of ZE-MHDVs supported by a phase-in strategy against a straightforward, linear deployment assumption. The phase-in curve is pegged against an assumed linear vehicle adoption rate, which would total likely adoption population assumed by recent EPA regulations.

Figure 8. Rapid, Extensive Market Penetration Supported by Phased Buildout of Infrastructure

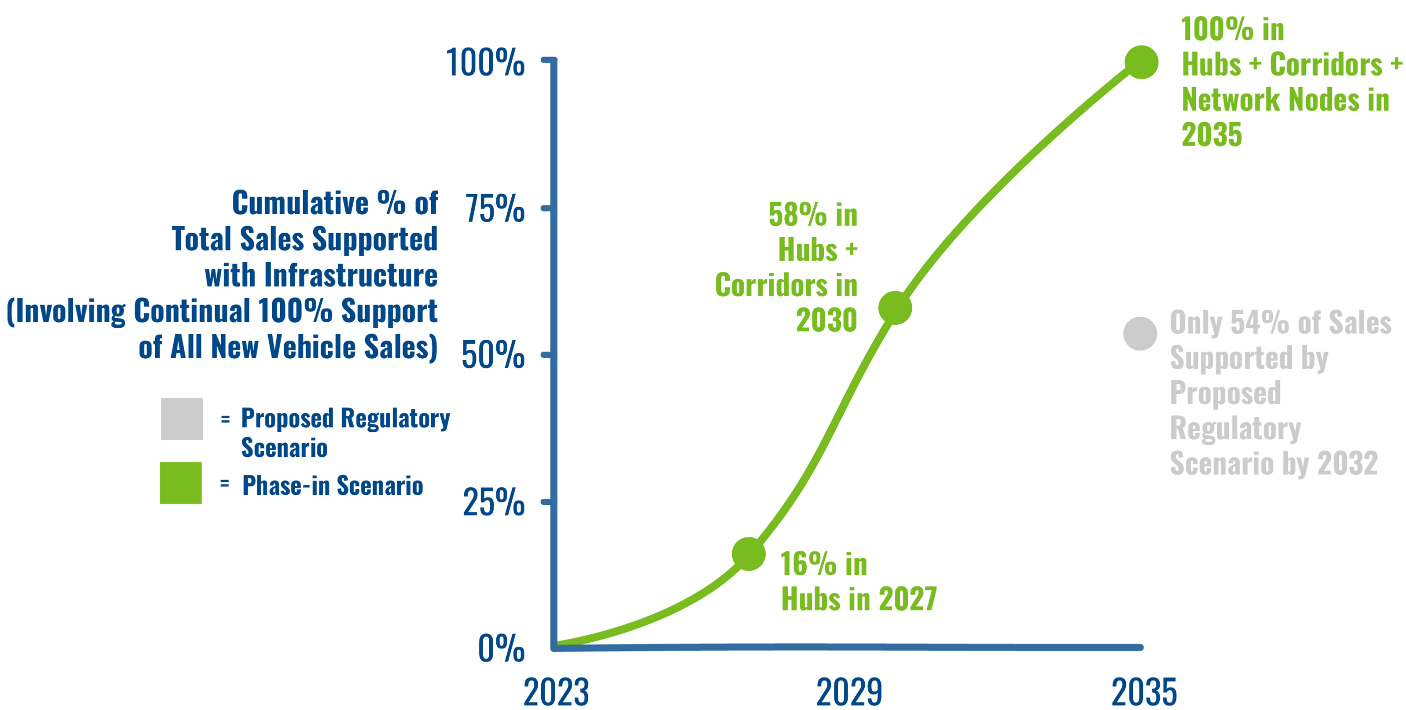


Figure 8 shows how, at all times, 100 percent of vehicles are supported by infrastructure but in very different ways. Initially, because buildout does not occur everywhere, deployment in the phased scenario is less than in a linear scenario; later, more deployments occur at a steeper rate, building off initial deployments. Even later, the curve smooths out, while still accommodating a higher overall percentage of the total number of Global MOU sales targets.

While the challenges involved in building out this scenario should not be underestimated, integrating spatial determinants of ZE-MHDV introduction along with timing priorities driving the use of infrastructure can support very sizable market penetration. The next sections discuss the deployment scenario results in depth and consider where industry assumptions were accounted for or where the scenario was limited in its considerations. In this way, this study shows how the phase-in scenario models one possible deployment pathway but contains a framework for supporting aggressive U.S. ZE-MHDV penetration rates generally. In sum:

- Energy demand will be geographically distributed where the transportation network will see deployment of ZE-MHDVs, and management of net demand can be met by a variety of energy system improvements.
- Deployment of infrastructure to meet this demand can be phased to target priority areas when and where infrastructure is needed first, while maintaining a rapid deployment rate that meets an aggressive demand.

II. When Buildout Will Happen: Prioritizing Areas

This analysis shows that phased deployment can manage timelines and maximize utilization, even at an aggressive ZE-MHDV penetration rate. New ZE-MHDV introductions will be served by targeted, rather than uniform, deployment. The following section discusses in more detail 1) how this important dimension of buildout is captured in this assessment, 2) how it reflects industry strategy, and 3) where other strategies involving prioritizing deployment areas for nearer-term vs. longer-term investments may also be at work in investment planning (though they may not be captured in this study).

Overcoming Barriers to Availability

Three central issues are often cited in discussion of infrastructure deployment barriers:

- Lead times for installation
- Energy capacity and volume concerns
- Unforeseen costs

This analysis does not underplay the importance of these barriers, which constitute considerations important to fleets (Electrification Coalition, 2020). At the same time, the last section's discussion of phasing shows that these barriers may not primarily arise *wherever* and *whenever* one fleet seeks to electrify. Rather, barriers appear *when* and *where* the maximum number of ZE-MHDVs are unable to maximize potential utilization of equipment.

In this sense, prioritizing areas for infrastructure buildout is a key strategy for overcoming barriers generally. In other words, deployment will not happen at first everywhere but "where it makes sense" with respect to maximizing infrastructure utilization (North American Council on Freight Efficiency, 2021).

Areas identified as priorities for rapid and concentrated deployments shift buildout ahead in time and away from areas where ZE-MHDV adoption rates are less important. They also concentrate utilization within geographies. First-mover-area infrastructure thus has the potential to be utilized more in the near term and possibly more efficiently over the life of its deployment. The pace of infrastructure deployment then precisely matches demand by shifting deployment to where there is the *most need*.

To establish priorities, this analysis used a spatial scoring of areas based on four factors with the potential to drive utilization, already mentioned above in the last section's discussion of priority areas for deployment. Table 5 below summarizes the factors and data sources used to understand the deployment geography in this manner. The following discussion will expand on and illustrate these priorities.

Table 5. Priority Factors

Factor	Description	Data Sources
Identified investment areas	Whether an area has already been indicated as a priority for investment by industry or by supportive federal money	CALSTART industry conversations; public announcements
Political, social, equity priorities	Whether an area will have adopted ACT, has signed on to or supported the Global MOU, is a major area for freight, or would benefit from investment in terms of air quality	Census data; industry data; North American Council on Freight Efficiency High Potential Regions Report
Economic clustering	Whether there is a concentration of sectoral activity (i.e., firm location and growth) in MHDV transportation services (such as warehouses, logistics, or other sectors)	U.S. Census NAICS codes and data
Energy	Whether likely grid improvements will be present in an area in the future	NREL Levelized Cost of Energy data

Examples in the Real World

Prioritization reflects real-world strategy and coordinated investment trends by major industries around high-potential areas.

Investment Priorities

Major fleets have service territories they will need to electrify in cooperation with infrastructure providers and energy services. Fleets are not, then, agnostic about the locations of investments both in their depots and along the larger transportation system.

Within depots, fleets are increasingly engaged in both coordinated charging between two sites and out-and-back operations, which would be primarily useful once opportunity charging is installed. In a striking role reversal, some charging site developers have made major investments in establishing their own fleets and have started deliveries. This reversal underscores the normal logic of fleet transition; as fleets consider the routes that could be electrified, they specifically begin to prioritize the coordination among their locations and the facilities they serve.

Accordingly, announcements in pull-through charging investments have targeted these key territories. BlackRock, Daimler, and NextEra have announced Greenlane, a $650 million joint venture to build out key corridors breaking ground this year; the three areas it identified publicly, which gesture to the West Coast, the South, and the East Coast, all specifically target service territories of major fleets operating in those areas (NextEra, 2022). TeraWatt announced that it would use $1 billion in seed funding to build charging stations from Los Angeles to Texas; this overlaps with the territory of major fleets moving goods specifically from the Ports of Los Angeles and Long Beach toward the Texas Triangle (TeraWatt, 2022). It also overlaps with the territory of fleets in Texas and which travel into Texas from Oklahoma, from Atlanta, or along the Gulf Coast.

Recent state and federal government funding has been influential for driving initial partnerships of investors and public agencies. Accordingly, states and charging site developers are working with fleets whose service territories are along these corridors to coordinate an infrastructure buildout strategy. These decisions, in short, are strategic and involve a major focus on making important geographies for fleets electrify first, rather than attempting to electrify the entire country at the same pace.

Political and Social Priorities

Political priorities are important factors. States adopting ACT regulations are often supporting them with incentive opportunities or coordinative activity to further leverage new federal funding for charging infrastructure. These constitute favorable environments for charging. The states themselves constitute priority geographies for fleets looking to reduce upfront costs of infrastructure in their larger deployment planning. States also determine priority areas to support via infrastructure investment and to align with other statewide strategy documents. Again, the roadmap to ZE-MHDV adoption is not uniform but instead tied to goals.

California in particular develops strategy documents to align infrastructure deployment to support key fleet territories within several public plans, such as CEC's Statewide Infrastructure Assessments, the California Public Utilities Commission's (CPUC's) Freight

Infrastructure Planning Process, and the California Transportation Commission's Priority Freight Corridor Designation process (CEC, 2018; CPUC, 2023). Each of these larger efforts prioritize specific areas and identify key measures, including energy rates and policies, which can assist deployment. Texas has adopted major public charging rate design legislation in a similar fashion, with key locations in mind and planned. New York is presently engaged in a similar commercial vehicle infrastructure proceeding. Another excellent example is Colorado, which has just adopted ACT. Colorado developed a robust set of climate and utilities policies in 2019, captured in its Electric Vehicle Plan, which worked to support goals of the electrification of key areas for commercial vehicles (Colorado Energy Office, 2020).

The number and pacing of these sites are directly tied to larger state agency initiatives to realize certain statewide climate plans, transportation efficiency improvements, and other broad statewide goals. Prioritization also features prominently in regional plans for goods movement, with the location of key areas for initial deployment captured in supporting studies.

Economic Clustering

This analysis reflects how commercial fleets are often located in clusters of similar firms within their industry, or in key locations that effectively integrate with the land uses and economy of the area (Delgado et al., 2014). Many fleets are increasingly engaged in efforts to electrify not just their own depot but a larger economic cluster. Fleets next to ports, for instance, will be engaged in many complicated collaborative planning and coordination exercises in order to identify and direct investments in their facilities and into the surrounding area, which will be important for their electrification efforts. Some of these plans—such as in coordinative efforts led by the Port of San Diego—involve discussion of the placement of shared charging resources or public facility deployments, which would assist the development of this cluster as a whole.

Fleet deployments are often integrated within comprehensive and long-term facility development plans, which afford a managed and phased-in approach to interconnection issues and close coordination with utilities. They also allow fleets to integrate electrification within larger sustainability planning efforts in cooperation with demand aggregative capabilities of utilities. In particular, vehicle-to-grid technologies offer methods for integrating fleet, facilities, and the grid directly, as well as managing demand in real-time and even in advance with utilities through demand response technologies and charging-discharging scheduling. Sites with these sorts of capabilities, or the potential to grow into such capabilities, serve as a major priority for electrification over others.

In addition, supportive public sustainability strategy frameworks and regional emissions regulations increasingly anticipate specific land use- or facility-based integration measures as a means for fleet compliance with emissions reduction targets. The California Sustainable Goods Movement Action Plan, California's ACF rule regarding drayage vehicles and their traffic near ports, and the South Coast Air Quality Management District's (SCAQMD's) Warehouse Indirect Source Rule all focus on the phase-in of new infrastructure from a holistic facility approach to manage emissions (CARB, 2016; CARB, 2022; SCAQMD, 2021). All these strategies and regulatory approaches, many of which are currently being replicated or will likely be replicated in ACT states, involve the prioritization of areas to ensure the success of fleet transition, rather than leaving the general location of infrastructure up to chance.

Energy Markets

This analysis reflects how fleets and infrastructure developers also prioritize areas based on energy market considerations. One factor generally is utility strategies for investments to support charging infrastructure. While seeking out areas for prioritization will drive more need for grid upgrades into certain areas—particularly the installation of new transformers—the coordination around the nature of these upgrades in such areas will be more robust and more efficient. The upgrades themselves will be utilized in a more efficient manner and provide an opportunity for new transactive service capabilities that will allow users to talk to each other (PNNL, 2022a).

Regional cost of energy is a potential driver of area prioritization for fleets that this analysis seeks to capture. The price of energy has been considered a major factor in investment decisions in fleet transition and larger charger deployment coordination efforts in which CALSTART has participated, and is acknowledged to be one of the major factors in maximizing utilization of charging (Phadke et al., 2021). Current statewide holidays on peak charging—such as those instituted by major California utilities—and innovations in rate structure attest to the importance of this factor. However, cheaper energy in general will also be a factor in lowering cost of the energy delivery systems.

In conversations with utilities as part of its planning activities for corridor development and in working groups on interconnection, CALSTART has witnessed utilities taking a variety of new strategies to speed up interconnection that involve the prioritization of particular areas. Many utilities look forward to utilizing energy infrastructure in key locations where already existing assets can be identified by a developer; they also look forward to a development in a wide array of energy services between their distribution network and customers, as well as planning upgrades and working more proactively.

In both cases, interconnection queues are managed not just through overcoming physical barriers in capacity and reliability but by developing new business models that are tailored to the market for mobile distributed loads that ZE-MHDVs compose. Fleets will be able to prioritize their transition to ZE-MHDVs where fleets, utilities, and energy service providers are all working toward this goal and where the market is particularly well developed to witness this sort of innovation.

Across all of these examples, the prioritization of key areas because of particular locational advantages either to a fleet's operational needs, to the sector, or to others in the space drives investments into those areas. These examples show that investment can create the potential for regional synergies in deployment, further signifying an area as a priority.

Examples in Analysis

In the optimized scenario modeled, some of these factors are reflected in the general distribution and extent of first-mover clusters and the key supportive corridors, which are identified in this section. Areas with clear industry interest from public statements have a high connection with the annual growth rate in ZE-MHDVs as projected in this analysis and serve as an important prioritization factor. These areas are:

- West Coast (I-5 in California, Washington, Oregon)
- East Coast (I-95 in New Jersey, New York)
- The Texas Triangle (I-10, I-35, I-45)
- Southwest (I-10 in Arizona, New Mexico)
- Rocky Mountains (I-70, I-25 in Colorado, Wyoming, Utah)
- The Midwest (I-80 from Ohio through Illinois)

These areas are supported by the recent Department of Energy Zero-Emission Freight Corridors (U.S. Department of Energy, 2023).

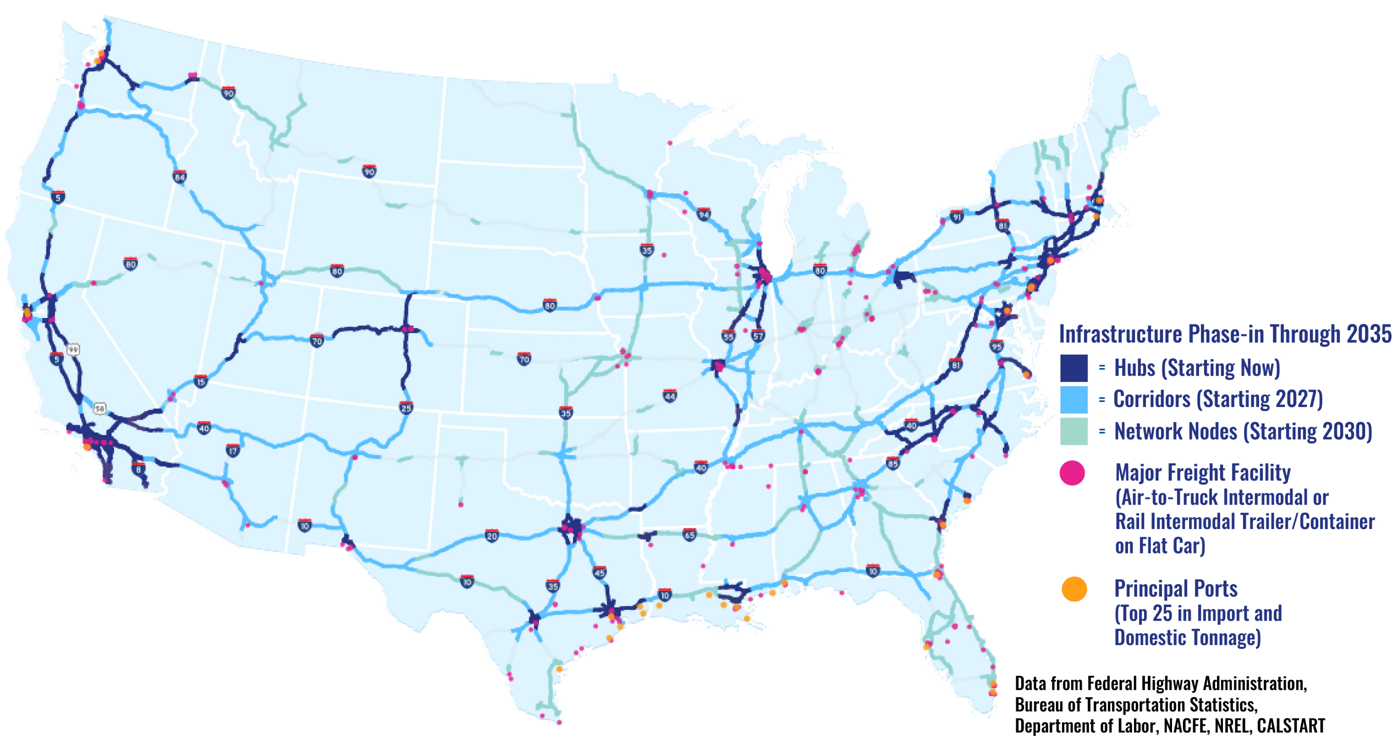
High policy priority areas include all of the signatories to ACT and those considering. In fact, this analysis highlights a very high connection between planned deployment volumes and areas with projected ZE-MHDV sales introductions.

Industry clusters in logistics and warehousing are centers in which annual growth in ZE-MHDV on-road travel concentrates. These include transportation and logistics and warehousing centers, such as the San Bernardino Valley in California, but also areas outside of major ports, including those in Oakland, the Puget Sound, and major East Coast ports such as those in Georgia, Virginia, New Jersey, and New York. Major logistics centers and hubs supported by intermodal travel appear as well in this analysis, particularly Chicago and Atlanta.

Levelized cost of energy of renewables and distributed energy resources were used to establish priority areas where energy distribution upgrades supportive of ZE-MHDVs will be likely, and thus be a priority to fleets seeking to electrify. This data found that a larger share of growth in distributed energy will fall generally across the Southwest and in the West, as well as certain areas of the Gulf Coast and Midwest through 2040.

To illustrate the combined prioritization of key areas and how it arises from the factors outlined in Table 5 above, Figure 9 shows the regional variation with contextualizing data concerning major freight facilities and ports.

Figure 9. Phase-in Priority Areas and Context



Considering the map above, priority factors can help explain regional specifics that arise from phasing in infrastructure, as well as the overall plausible roadmap for transformation for each region.

Mid-Atlantic / I-95

A high concentration of states adopting the ACT rule and federal money for a corridor (I-95), plus industry clusters of warehousing and connection to ports allowing closer coordination around I-95, make policy and industry clusters the focus of infrastructure buildout planning in this area. Many deployments centering in clusters and hubs may arise at first, where little open-road charging infrastructure envisioned for a national network is necessary to connect major hubs and key facilities like ports. Instead, investments will be utilized to connect key depots together, share demand, and accelerate investment.

Southwest / I-10

Huge advantages in a greater share of distribution grid infrastructure from solar and distributed energy resource growth onsite make this region a priority area; freight travel connected to high energy demand hubs also make it likely that development occurs to connect major areas along a potential corridor. The low concentration of supporting industries except at either the Los Angeles or Texas ends of I-10 makes heavy buildout along corridors necessary to support the needs of ZE-MHDVs.

Midwest / I-80

This is an important corridor for the last phase of investments: the national network. Filling in federal connectors to airports and the hubs coming off of West Coast freight travel does not just happen but forms a targeted effort in the later part of this projected timeline. While it may not score high in terms of certain future distribution system growth advantages, investments in key facilities of national importance, together with the efforts to build out national charging, benefit the region.

Takeaways

The major takeaways from the prioritization of areas are threefold:

- By shifting investment into priority regions, more ZE-MHDVs can be supported in less time and for less overall investment.
- Key priority launch areas will form around areas where industry can leverage investments, where political and social priorities create a favorable policy atmosphere, where industry clusters form, and where energy is cheap and has a high potential for distributed grid investments to take off.
- By prioritizing key areas and regions, those areas become integrated and can realize connected utilization efficiencies.

III. How Buildout Will Be Efficient: Site Configurations

The following section discusses how this study integrated strategies to reduce delays in deployment and manage specific risks associated with infrastructure availability by considering deployment configurations.

Overcoming Barriers to Utilization

Lacking infrastructure where and when it is needed is not the only barrier to deployment but fits within the larger picture of an operational shift that fleets are planning for and negotiating (RMI, 2021). This analysis addresses three potential difficulties that fleets are negotiating:

- Energy availability potentially lagging behind vehicle introductions
- Reliability of energy infrastructure
- Uncertain utilization forecasts for shared infrastructure

For the purposes of this analysis, these difficulties were translated into problems that capture how a site can be configured for maximum utilization.

While low utilization in terms of shared infrastructure is a well-understood concern of public charging deployment, the problem should be expanded and understood to encompass many of the issues generally regarding sites. The energy delivery system necessary to support the introduction of ZE-MHDVs is similarly out of balance if a site is not able to deliver power to them or if it is doing so unreliably. Additional components of the energy delivery system besides the charger itself—such as operational or technology factors that manage the site's power—should be integrated into assumptions about how the charger is used and is able to be used more over time.

Accordingly, this analysis considered deployment *configuration* within an analysis area, which introduces potential effects of optimizing charger power ratings for utilization or reaching a certain amount of throughput per charger necessary to optimize the overall relationship of vehicle to charging infrastructure. This analysis assumed that there is a constant industry pressure to optimize configurations in three ways.

First, to address how fleet management services within depots are increasingly used to negotiate infrastructure deployment barriers, this analysis assumed that charging preferences will not be uniformly tailored to vehicle routes but instead will trend toward efficient charging ratings to accommodate the introduction of ZE-MHDVs. Fleets use a mix of higher power and low-power chargers and optimize based on the site's flexibility to drive up utilization.

Accordingly, this analysis also assumed that, especially in priority areas, potential for throughputs per charger can be higher or lower than one vehicle per day. Infrastructure can be shared through a depot-shared system or a depot Charging-as-a-Service (CaaS) system; additionally redundant infrastructure can be built to increase reliability without necessarily creating a higher load on the grid if the charge is managed. The specific assumption used in this analysis was that, except in the case of dedicated public chargers, most chargers are dedicated chargers for one vehicle but can, especially if they are at a higher power rating, charge other vehicles as well.[5]

Third, this analysis assumed that onsite battery storage constitutes a real feature of many future deployments, and that this makes available additional deployments or increased utilization through more flexible site-level management. More volume available to chargers to utilize and manage can lead to higher utilization rates per site.

Examples in the Real World

These assumptions account for the real-world practice of building out infrastructure such that it can be managed by control systems or by site-level management adjustments. The overall energy needs of the energy delivery system can be adjusted so that vehicles can be introduced but not necessarily create an unsustainably high load. This allows the introduction of new vehicles over a predictable timeline while distribution infrastructure comes to meet the site.

Managed charging is a major strategy in feasibly deploying sites while the grid is built out. This can involve 1) improving utilization rates per deployed vehicle through software and operations, and 2) the improvement of overall energy load to allow for a deployment strategy. Current providers of managed charging systems provide services to fleets, which actively manage the energy needs involved in building out a fleet's site.

Four real-world components of this solution were included in this assessment. Active load management services, onsite storage, mobile and temporary infrastructure, and shared infrastructure can be combined—and coordinated—into a site operations regime that takes advantage of charge management software to keep energy demand within acceptable limits of capacity while the latter is expanded or built out. A fifth related

[5] The difficult problem of queuing is not factored in this analysis; rather this analysis assumes conservative throughputs and confines these mostly to shared public chargers.

component is high-power charger integration on sites, which will provide increasing options within sites that need higher throughput in general.

Load Management Services

Load management services can manage the introduction of new loads at facilities while grid capacity is built out. A combination of charge management software and a broader analytic services suite can be actively integrated into facility expansion planning so that recharging infrastructure to support a fleet can be continually installed while staying underneath grid capacity as the latter expands and is upgraded.

One interesting example of successful load management service comes from EO Charging, a UK company that is expanding its presence in North America. EO currently manages the charging operations for several large fleets, including more than 5,000 Amazon commercial electric vehicles in Europe, primarily delivery vans but including medium-duty trucks. Their site design and operation enable accelerated truck deployments and manage utility capacity delays via smart managed charging and a mix of flexible charging rates to meet fleet operational requirements, site capacity limits, energy storage, and pricing considerations. In conversations, the group noted the system has been delivering consistent 99+ percent reliability/uptime (EO Charging, 2023).

Onsite Storage

Sometimes coupled with onsite generation, onsite storage allows a more flexible load to be managed by the control system or utilized as redundancy. Charging infrastructure is now often dispatched together with battery packs. New announcements in charging storage tailored for commercial vehicles are happening apace, and some are positioning themselves as useful for not only depot but also corridor charging (ChargePoint, 2023).

Another solution is battery swapping, which places batteries in a bank and allows charging to take place at low speeds throughout the day.

Mobile and Temporary Infrastructure

CALSTART recently performed an inventory of temporary infrastructure solutions that could assist in the deployment of vehicles and which some vehicle manufacturers are coupling with sales of new ZE-MHDVs to bridge the gap between when energy delivery system upgrades and the actual infrastructure are deployed. Because temporary infrastructure is assumed to effectively deliver energy without creating a permanent need, it was not factored into this deployment assessment. Nevertheless, it can remain a pathway to react to the introduction of ZE-MHDVs or bolster reliability. Temporary and mobile charging solutions can usually be installed and inspected in less than one month and currently cost under $200,000, while saving fleets permitting and installation costs in the short term. FreeWire, DANNAR, Eaton, BP Pulse, Proterra, Veloce Energy, Beam, GM, Lightning, and Voltera all manufacture systems, some for under $100,000.[6]

Shared Infrastructure

The final strategy is the sharing of charging infrastructure, whether at the depot or in a public charging site. At the depot level, several efforts are underway to aggregate demand among multiple fleets at a co-located site, or to coordinate one fleet across multiple locations. CaaS strategies are now the basis of many planned depot charging projects within depots; vendors have adopted reservation systems or per-charge solutions which can be built out to charge a co-located set of fleets and in many ways can be integrated into new facility design and construction, especially in the logistics and warehousing space, shortening timelines and giving predictable coordination to utilities (CALSTART, 2021c). This is a companion, outgrowth, and driver of clustering, as explored in Section II above.

Shared accessible infrastructure is also a supportive system, which is accounted for both at the depot level (as mentioned above) and in public charging. Major investments on corridor-level pull-through charging by companies show that this is a model with viability and that at scale could produce real effects. In this analysis, it was not necessarily considered a factor that removes a need for return-to-base charger deployment at the depot level to support vehicles. However, it does introduce a play between the charging needs for vehicles continually and the chargers continually within a depot, and if present in areas, may allow depot charger utilization to increase.

Higher Charging Power

Higher charging power is quickly becoming a reality. CALSTART is engaged with the Electric Power Research Institute on a project to deploy higher-power charging approaching megawatt levels, and manufacturers such as ABB and Siemens are both testing and nearly ready to offer potential solutions on the market. Charging utilization rates jump extremely high with the introduction of higher power charging. A 15- to 30-minute charge of a major Class 8 truck is theoretically possible at these rates, as well as throughputs which dramatically increase the availability of a charger to potential vehicles.

The effects of higher power charging in this study were not considered beyond a higher assumed utilization rate among public chargers and a total assumed share of deployment configuration, which is very consistent with the high use of high-power charging. However,

[6] Many of these systems can be rented or leased for short periods of time to minimize costs for the fleet (allowing them to be utilized only until permanent solutions can be deployed and then transferred to a new site, where another fleet can take advantage of the same unit).

innovative deployments to handle energy needs should also be noted, including the potential of connecting directly to sub-transmission level medium-voltage lines and reducing the need for step-downs.

Examples in Analysis

This study forecasts that battery packs will be used in some form on many sites (i.e., 50 percent) in both hubs and clusters and along corridor sites. On other sites on the national network, they will be widely used (i.e., 50 percent of deployments). This analysis did not assume that battery packs will be used as part of microgrids or distributed energy generation, which may offset peak loads; however, the assumption was made that in any case they will be deployed as an add-on that forms part of a site's energy demand management system and unlocks the availability of one additional charger per vehicle per site by creating utilization flexibilities. This was built in as a cost increase per deployment according to the share allocated to each specific geography. A long duration (> 2 hour) battery storage system of 650 kilowatts (kW) was assumed, and this analysis used both standard deployment configurations for charging rows of commercial vehicles and industry costs on storage derived from recent cost assessments (Energy Information Administration, 2021; PNNL, 2022b; NREL, 2021). While this increases the costs of an individual deployment in this scenario, it enables many charging strategies and deployment configuration optimizations. This analysis did not consider potential cost savings on energy peak demand, but these are also likely significant.

Accordingly, this analysis also assumed that shared charging will be prominent in priority hubs and clusters and somewhat on corridors; nearly 50 percent of chargers will be as shared in those areas in some way—if only by using two ports—while on sites along corridors a similar percentage of chargers will be shared in some way. This analysis did not assume that sites composing the national network will utilize shared charging. Instead, it was assumed that sharing will add additional utilization to the charger of 50 percent, which ultimately reduced the total costs over the maximum scenario.

Furthermore, it was assumed that public charging will become widely available, especially in areas along corridors and the national network. Utilization of chargers in public sites is very high, and this analysis assumed that they effectively double or triple the utilization of a charger per day. This is a conservative estimate, as calculations involving public chargers can, depending on the need, yield a utilization rate of twelve or even sixteen vehicles per day. These estimations follow Lawrence Berkeley National Lab at this time, but future iterations will make room for high-power charging, which will have even higher utilization rates (Lawrence Berkeley National Lab, 2021). Though most public sites have a more delayed deployment phase-in in this assessment, and assuming only 10 percent of hubs and 10 percent of sites on corridors are public, and that half of sites along the national network are public, this approach produces additional total cost reductions.

Takeaways

The major takeaways from this discussion of site configuration are threefold:

- Utilization is the primary factor in establishing optimal site configurations, and different priority launch areas have optimized site profiles that maximize utilization.
- Phasing in strategies will focus on maximizing charger utilization to manage energy demand increases.
- If utilization is optimized, the costs of infrastructure per vehicle can be lower and the buildout rate can still proceed rapidly.

IV. Conclusions

The previous sections discuss a market-driven, overlapping, and concurrent growth of a supportive ZE-MHDV ecosystem in a *phased transition*. This final section summarizes conclusions and suggestions for how this analysis can support a framework for future infrastructure deployment.

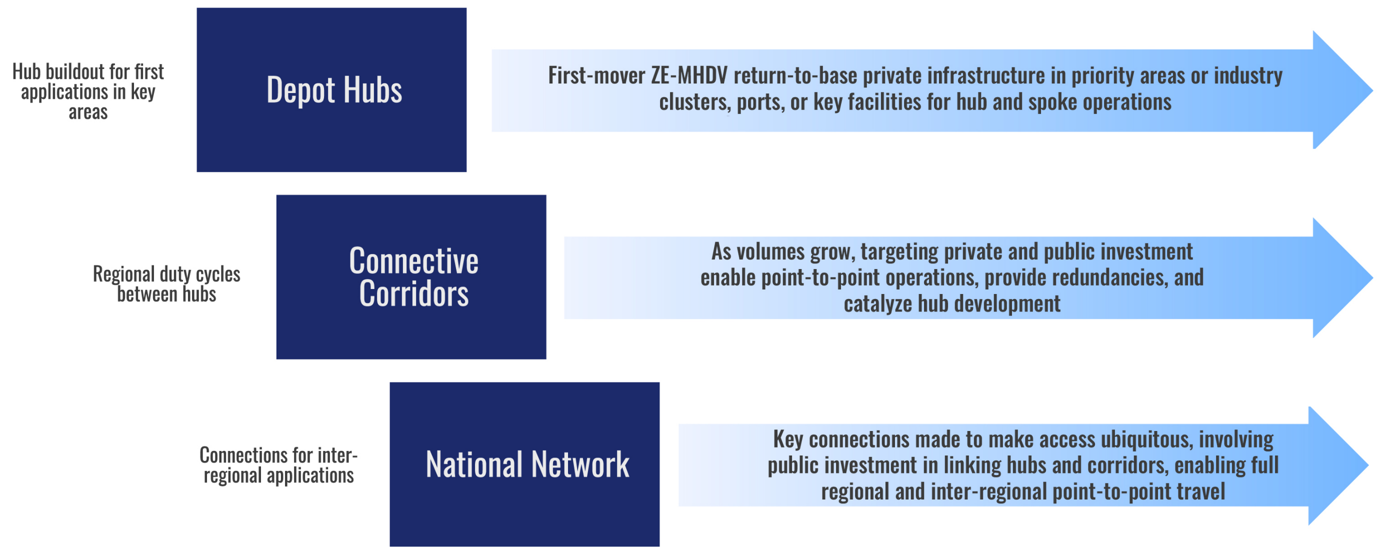
Discussion: Network Effects and Further Research

Network Effects

Many existing models project infrastructure needs by scaling up infrastructure needs analyses that utilities and fleet transition specialists are now performing on individual fleets within their depots. By contrast, this analysis represents a systems approach to energy transitions. It is oriented toward capturing effects that these depot-focused models mostly aggregate or ignore, and which arise as soon as a fleet is considered within a larger combined travel and energy market.

Some of these effects have been described by CALSTART in previous papers as arising within the "market gradient" for new and advanced technologies, and still apply even as all ZE-MHDVs are now mature and ready for adoption in all applications (CALSTART, 2021b). As deployment progresses through the phases described in this study, the market will continue to involve innovations and learnings, and the investment of capital in infrastructure will seek high leverage and benefit opportunities. Progression through the phased transition can be summarized in Figure 10.

Figure 10. Infrastructure Phase-In Progression



This figure updates previous versions of CALSTART's assumptions regarding the deployment of vehicles in light of the findings of this working paper (CALSTART, 2022b). It brings together several axes of change seen in Figure 2 above, including vehicle technology, duty cycles, and fleet management scenarios. But it also summarizes how the findings from this study compose a dynamic picture of the future of the infrastructure and vehicle markets, involving coordination, learning, and overall technology cost reductions.

Coordination and Learnings

This analysis makes room for implementation efficiencies characteristic of a dynamic technoeconomic shift. These efficiencies—which are already happening—are assumed to be a key driver of prioritization and maximized utilization from site configurations. Commercial vehicle deployments are being served by make-ready programs within specific utility territories and exhibiting a geographic prioritization, showing that this prioritization of first-mover regions is both possible and occurring. In general, this analysis was framed to capture this effect, which can increase and streamline infrastructure delivery processes, as well as drive overall distribution system modernization and resiliency. Where similar needs are catered to, more refinements will emerge.

Capturing these dynamics is also important to understand that risk reduction will cascade across an increasingly energized transportation system. Many of the utilization efficiencies in prioritizing areas and establishing high-utilization configurations outlined in Section III above will involve advance planning and the management of both net demand and any grid impacts. But again, prioritization can assist. In key areas, services are now provided by a suite of well-established service providers and consultants, which can dramatically reduce the potential of a new deployment triggering unforeseen major upgrades. Microgrid Labs, for instance, provides advanced simulation of grid needs for medium-duty fleets as well as many other commercial vehicle applications; in the course of their analyses, they identify and flag grid reliability needs and grid upgrades necessary for a fleet's electrification well ahead of time, reducing the potential for surprises. Comparable services are now being offered by major firms like Arup, Edison Energy, ICF, GNA, and Parsons, to name a few.

In addition, in conversations with CaaS providers and site developers, CALSTART has learned that these evaluations are regularly developed as a way to assess site potential as well. The growth of a transportation-energy integration industry—which features some site developers with data-center development experience—and the increasing sophistication of this planning for fleets make coordination with utilities easier and open up a window of multiple options for interconnection. Transitions can then pace at the rate responsive to the grid's upgrade timelines and needs.

The extensively studied and generally predictable dynamics of travel markets will allow for advance planning for upgrades. To prioritize areas generally is to extend from the fleet's operating territory to both the travel market and the grid.

Technology Diffusion

These efficiencies will lead to decreases in technology costs, which lower the levelized cost of charging infrastructure (Borlaug et al., 2020). While many factors involved in manufacturing and in technology diffusion and market acceleration in infrastructure can lead to cost reductions, these assumptions were mainly based on dramatic cost reductions in comparable industries and in the distribution system. For instance, analyses show that capital costs across energy delivery infrastructure have been subject to great changes, such as in solar technology, and not to major increases except through extreme market changes.

CALSTART has tracked both market growth in energy infrastructure solutions and infrastructure costs in this space, both within research targeting market acceleration and within projects involving the administration of state incentive programs for EVSE. A reasonable technology reduction cost was considered between 4 percent and 7 percent over the course of this analysis within the priority areas. In this way, the analysis accounted for how industry will be creating shared solutions together, especially in priority areas. Over the timeline of this analysis, total capital costs were reduced 11 percent in the resulting scenarios.

Overall Cost Reductions

Overall costs are included in Table 6 below.

Table 6. Costs ($ billions)

Area	Phase 1	Phase 2	Phase 3	Total
Cluster	$10.0	$37.2	$11.7	**$58.9**
Corridor	$1.9	$7.2	$5.6	**$14.7**
Network	-	$0.5	$5.2	**$5.7**
Total	**$11.9**	**$44.9**	**$22.5**	**$79.3**

These costs are similar to those projected by other studies (ICCT, 2023). Note that these figures could be significantly reduced, however, if 80 percent of costs are be borne by private investment, especially along key clusters and corridors where federal funding currently exists. For this reason, potential funding leverage was factored into prioritization in Table 5 above.

Several important network effects can result from these costs. First, costs are shifted into areas where the highest priorities in the overall deployment are located. Second, they increase when corridors connect to those areas and where national nodes are added on to support them. It is likely that these costs can be optimized further through the adequate establishment of the interaction of sites within each priority launch area. That is, by growing smartly in key areas, and then managing the distribution of travel within these areas between sites, further buildout of sites will be able to take place more or less cheaply as the market grows and ZE-MHDVs penetrate more deeply into that market.

In short, fully managed clusters and integrated, intelligent travel corridors that maximize site level utilization even further could reduce costs overall through a flywheel-like effect. This effect, which is truly visible when a systems approach is taken and costs are not accounted for by simple aggregation, will be explored along with the other network effects mentioned above in future versions of this working paper.

Recommendations

Based on this assessment, aggressive ZE-MHDV penetration rates can be accommodated by a buildout of energy delivery infrastructure if a phase-in method and strategy is taken seriously for this deployment. Previous CALSTART discussions on infrastructure recommended major coordinative actions necessary among stakeholders in the transition to support ZE-MHDV infrastructure buildout (CALSTART, 2020):

- Conduct road mapping and anticipate emerging demand.
- Develop competitive utility rate structures.
- Create favorable utility investment regulatory frameworks.

On the basis of the above analysis, this list can be extended to include the following:

- Forecast high-level energy needs using a phase-in approach sensitive to the anticipated distribution of energy needs in specific priority launch areas.
- Coordinate investments around priority launch areas that will accommodate vehicles first, designating them with specific prioritization factors including industry clustering, investment leverage potential, supportive policy, and energy system development potential and costs, as in Table 5.
- Encourage practices and policies to support coordination around higher charger utilization.
- Plan rapidly for grid modernization around transportation and energy system integration.

Future Work

CALSTART is engaged in work to bring together and advance ideas related to address energy demand issues in this scenario for probable demand growth. Further investigation of flexible interconnection, bring-your-own-device strategies, time value rates, performance-based regulations—which are critical to some of the concerns developed here—will be the subject of future research to be integrated into this paper and other related efforts to show how phased infrastructure buildout could meet demand for ZE-MHDVs.

References

Borlaug, B. et al. (2020). National Renewable Energy Lab. "Levelized Cost of Charging Electric Vehicles in the United States." Retrieved from: https://www.osti.gov/pages/biblio/1808204

California Air Resources Board (2016). "California Sustainable Freight Action Plan." Retrieved from: https://ww2.arb.ca.gov/our-work/programs/california-sustainable-freight-action-plan

California Air Resources Board (2022). "Advanced Clean Fleets Regulation, Drayage Truck Requirements." Retrieved from: https://ww2.arb.ca.gov/sites/default/files/barcu/regact/2022/acf22/acffroa3.pdf

California Energy Commission (2021a). "Electric Vehicle Charging Infrastructure Assessment." Retrieved from: https://www.energy.ca.gov/programs-and-topics/programs/electric-vehicle-charging-infrastructure-assessment-ab-2127

California Energy Commission (2021b). "A Peek at Net Peak." Retrieved from: https://www.energy.ca.gov/data-reports/energy-insights/peek-net-peak

California Public Utilities Commission (2023). "Draft Staff Proposal: Zero-Emissions Freight Infrastructure Planning." Retrieved from: https://www.cpuc.ca.gov/industries-and-topics/electrical-energy/infrastructure/transportation-electrification/freight-infrastructure-planning

CALSTART (2021a). "Analysis of Public Sales Commitments of Medium and Heavy Duty Vehicle Manufactures and Expected Volumes." Retrieved from: https://globaldrivetozero.org/publication/analysis-of-public-sales-commitments-of-medium-and-heavy-duty-vehicle-manufacturers-and-expected-volumes/

CALSTART (2021b). "Assessing Technology and Market Readiness." Retrieved from: https://calstart.org/wp-content/uploads/2022/04/Assessing-Technology-and-Market-Readiness_Final.pdf

CALSTART (2021c). "Taking Commercial Fleet Electrification to Scale: Financing Barriers and Solutions." Retrieved from: https://globaldrivetozero.org/site/wp-content/uploads/2021/03/Taking-Commercial-Fleet-Electrification-to-Scale-White-Paper.pdf

CALSTART (2022a). "Infrastructure." Retrieved from: https://calstart.org/global-mou-on-ze-mhdvs-thematic-deep-dive-series-2/

CALSTART (2022b). "Global Roadmap for Reaching 100 Zero-Emission Medium- and Heavy-Duty Vehicles by 2040." Retrieved from: https://calstart.org/global-roadmap-for-reaching-100-zero-emission-medium-and-heavy-duty-vehicles-by-2040/

CALSTART (2022c). "The Beachhead Strategy." Retrieved from: https://calstart.org/wp-content/uploads/2022/04/The-Beachhead-Strategy_Final.pdf

CALSTART (2023a). "Roadmap to FCET Commercialization." Retrieved from: https://calstart.org/wp-content/uploads/2023/03/Roadmap-to-FCET-Commercialization.pdf

ChargePoint (2023). "ChargePoint and Stem to Accelerate Deployment of EV Charging and Battery Storage Solutions for DC Fast Charging." Retrieved from: https://www.chargepoint.com/about/news/chargepoint-and-stem-accelerate-deployment-ev-charging-and-battery-storage-solutions-dc

Colorado Energy Office (2020). Electric Vehicle Plan 2020. Retrieved from: https://energyoffice.colorado.gov/zero-emission-vehicles

Delgado, M. et al. (2014) "Defining Clusters of Related Industries." Institute for Strategy and Competitiveness, Harvard Business School. Retrieved from: https://www.clustermapping.us/content/glossary-terms

E3 (Energy+Environmental Economics) (2021). "2035, the Report: Distribution Grid Cost Impacts Driven by Transportation Electrification." Retrieved from: https://www.ethree.com/wp-content/uploads/2021/06/GridLab_2035-Transportation-Dist-Cost.pdf

Electrification Coalition (2020). "Electrifying Freight Pathways." Retrieved from: https://electrificationcoalition.org/wp-content/uploads/2020/11/Electrifying-Freight-Pathways-to-Accelerating-the-Transition.pdf

EO Charging (2023). "EO Unveils Complete Electric Vehicle Fleet Charging Ecosystem." Retrieved from: https://www.eocharging.com/stories/eo-unveils-complete-electric-vehicle-fleet-charging-ecosystem

Energy Information Administration (2021). "Battery Storage in the United States: An Update on Market Trends." Retrieved from: https://www.eia.gov/analysis/studies/electricity/batterystorage/pdf/battery_storage_2021.pdf

International Council on Clean Transportation (2023). "Near-Term Infrastructure Deployment to Support Zero-Emission Medium- and Heavy-Duty Vehicles in the United States." Retrieved from: https://theicct.org/publication/infrastructure-deployment-mhdv-may23/

Muratori, M. et al. (2023). "Road to zero: Research and industry perspectives on zero-emission commercial vehicles." Retrieved from: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC10192939/

National Renewable Energy Laboratory (2021). "Cost Projections for Utility-Scale Battery Storage: 2021 Update." Retrieved from: https://www.nrel.gov/docs/fy21osti/79236.pdf

National Renewable Energy Laboratory (2023). "Levelized Cost of Energy." SLOPE: State and Local Planning for Energy Data Viewer. Retrieved from: https://maps.nrel.gov/slope

NextEra Energy (2022). "Daimler Truck North America, NextEra Energy Resources and BlackRock Renewable Power Announce Plans To Accelerate Public Charging Infrastructure For Commercial Vehicles Across The U.S." Retrieved from: https://newsroom.nexteraenergy.com/news-releases?item=123840

North American Council for Freight Efficiency (2021). "Electric Trucks Where They Make Sense: High Potential Regions for Electric Trucks." https://nacfe.org/research/electric-trucks/#electric-trucks-where-they-make-sensehigh-potential-regions-for-electric-truck-deployments

Pacific Northwest National Laboratory (2022a). "DSO+T Expanded Study Results. DSO+T, Volume 5." Retrieved from: https://www.pnnl.gov/sites/default/files/media/file/DSOT%20Vol%205%20Study%20Results-Final.pdf

Pacific Northwest National Laboratory (2022b). "2022 Grid Energy Storage Technology Cost and Performance Assessment." Retrieved from: https://www.pnnl.gov/sites/default/files/media/file/ESGC%20Cost%20Performance%20Report%202022%20PNNL-33283.pdf

Phadke, A. et al. (2019). Lawrence Berkeley National Laboratory. "Why Regional and Long-Haul Trucks are Primed for Electrification Now." Retrieved from: https://escholarship.org/content/qt3kj8s12f/qt3kj8s12f.pdf

RMI (2021). "Steep Climb Ahead: How Fleet Managers Can Prepare for the Coming Wave of Electric Vehicles." Retrieved from: https://rmi.org/insight/steep-climb-ahead

South Coast Air Quality Management District (2021). "Warehouse Indirect Source Rule." Retrieved from: http://www.aqmd.gov/home/air-quality/clean-air-plans/air-quality-mgt-plan/facility-based-mobile-source-measures/warehs-distr-wkng-grp

TeraWatt (2022). "TeraWatt Developing I-10 Electric Corridor, the First Network of Electric Heavy-Duty Charging Centers." Retrieved from: https://terawattinfrastructure.com/ideas/i-10-electric-corridor/

U.S. Census Bureau (2023a). "U.S. County Business Patterns, 2021." Retrieved from: https://www.census.gov/programs-surveys/cbp.html

U.S. Census Bureau (2023b). "TIGER/Line Shapefiles." Retrieved from: https://www.census.gov/geographies/mapping-files/time-series/geo/tiger-line-file.html

U.S. Department of Energy (2020). "Modern Distribution Grid Guidebook: Volume I" Retrieved from: https://gridarchitecture.pnnl.gov/modern-grid-distribution-project.aspx

U.S. Department of Energy (2023). "Biden-Harris Administration Announces Funding for Zero Emission Medium- and Heavy-Duty Corridors." Retrieved from: https://www.energy.gov/articles/biden-harris-administration-announces-funding-zero-emission-medium-and-heavy-duty-vehicle

U.S. Environmental Protection Agency (2023a). "Proposed Rule: Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles – Phase 3." Retrieved from: https://www.govinfo.gov/content/pkg/FR-2023-04-27/pdf/2023-07955.pdf

U.S. Environmental Protection Agency (2023b). "Greenhouse Gas Emissions Standards for Heavy-Duty Vehicles: Phase 3: Draft Regulatory Impact Analysis." Retrieved from: https://nepis.epa.gov/Exe/ZyPDF.cgi?Dockey=P10178RN.pdf

U.S. Environmental Protection Agency (2023c). "MOVES3." Retrieved from: https://www.epa.gov/moves/latest-version-motor-vehicle-emission-simulator-moves

U.S. Environmental Protection Agency (2023d). "EPA Heavy Duty Technology Resources Use Case Scenario (HD TRUCS) Tool." Retrieved from: https://www.epa.gov/system/files/other-files/2023-04/hd-tech-trucs-tool-2023-04.xlsm

U.S. Federal Highway Administration (2018). "Highway Performance Management System Public Release of Geospatial Data in Shapefile Format." Retrieved from: https://www.fhwa.dot.gov/policyinformation/hpms/shapefiles.cfm

U.S. Federal Highway Administration (2023a). "National Highway Freight Network Visualization Tool." Retrieved from: https://fpcb.ops.fhwa.dot.gov/tools_nhfn.aspx

U.S. Federal Highway Administration (2023b). "National Electric Vehicle Infrastructure Formula Program Guidance (Update)." Retrieved from: https://www.fhwa.dot.gov/environment/alternative_fuel_corridors/nominations/90d_nevi_formula_program_guidance.pdf

Voltera (2022). "Voltera Launches as Turnkey Charging Infrastructure Solution for Companies Operating EVs, With Plans for Multibillion-Dollar Investment." Retrieved from: https://www.globenewswire.com/news-release/2022/08/09/2495043/0/en/Voltera-Launches-as-Turnkey-Charging-Infrastructure-Solution-for-Companies-Operating-EVs-With-Plans-for-Multibillion-Dollar-Investment.html

Appendix

Data Sources

For this study, CALSTART generally used publicly available data. For this reason, some of the estimates and derivations made are limited by the granularity of data available.

Energy Needs

Vehicle data was taken from the U.S. Highway Performance Management System (HPMS), using a base year of 2018 for projections. Additional contextual information was provided by the NHFN designation dataset. As noted above, areas outside the continental United States (including Puerto Rico, Hawaii, and Alaska, as well as other territories) were excluded from this analysis (Table A-1).

Table A-1. Travel Data Sources

Data	Specific Data	Source	Year
Travel data per segment	AADT, Operational Classifications, Segment Length	FHWA, 2018	2018
NHFN	Freight System Classifications	FHWA, 2023a	2023
EPA MOVES Categories	EPA Vehicle Categories	EPA, 2023c; EPA, 2023d	2023
Administrative Boundaries	Census TIGRIS Shapefiles	Census Bureau, 2023b	2022

Data included deriving travel per road segment in the form of annual average daily traffic for specific categories of vehicles within the HPMS dataset. These were cleaned with reference to both existing operational classifications relevant to the dataset and by validating against NHFN designations (allowing for differences within the designation process between 2018 and 2021). Vehicle classifications for MHDVs were crosswalked with vehicle categories in EPA MOVES. Administrative boundaries were taken from the most recent TIGRIS shapefiles.

Phasing

To determine how buildout phases would be split up (between Phases 1 through 3), the following datasets were used (Table A-2).

Table A-2. Prioritization Data

Category	Data	Source	Year
Industry infrastructure investments	Location of Deployment	Public announcements by NextEra, 2022; Terawatt, 2022; Voltera, 2022	2023
Federal investment areas	Federal FY 21-22 awards for U.S. Department of Energy corridor planning grant funds; Title 23 and NEVI Guidelines	Department of Energy, 2023; FHWA, 2023b	2023
ZE-MHDV potential	Priority Freight Regions (States)	North American Council for Freight Efficiency 2021	2020
Economic clustering	County NAICS Code Data	Census Bureau, 2023a Delgado et al., 2014	2022
Energy cost and grid improvement potential	NREL projected Levelized Cost of Energy data from 2020 to 2040 for solar and wind (commercial applications)	NREL, 2023	2022

Industry investment area data and federal investment areas were both developed into datasets by projecting assumptions of key locations onto the road network.

Industry Investment Area Data

Data on industry announcements has been tracked by CALSTART and was derived from public announcements. Five-mile buffer areas around the road network in the areas covered by the announcements were developed and reprojected to intersect with the grid and flag an area as a particular industry priority with the appropriate weighting.

Federal Investment Area Data

Federal investment areas were also taken from announcements. Major federal corridor planning projects to use Infrastructure Investment and Jobs Act funding were selected. A 5-mile buffer was placed around these corridor areas, and these areas were flagged as federal corridor investment priority areas and given the appropriate weighting (U.S. Department of Energy, 2023).

In addition, the National Electric Vehicle Infrastructure (NEVI) Formula Program enables states to designate sites eligible for public funding roughly every 50 miles (FHWA, 2023b). Fifty-mile sites were projected across the nation near the network in this study and designated as a priority with the appropriate weight.

Assumptions Data

Table A-3. Cost Data

Data Source	Specific Data	Source	Year
EVSE	Average per-vehicle EVSE costs	Borlaug et al., 2020 EPA, 2023a; 2023b Muratori, 2021	2020-2023
Onsite storage	Average onsite battery storage cost per vehicle	NREL, 2021; Energy Information Administration, 2021	2021

Approach

Energy Needs

HPMS 2018 vehicle activity data was used where the vehicle activity is available for both single and combination vehicle classes. These categories were aligned with EPA MOVES vehicle categories in a crosswalk. Data was prepared and validated against existing vehicle activity data and filtered for segments on the National Highway System Network, specifically the Primary Highway Freight System. The vehicle activity data was parsed as follows:

1. Vehicle activity data (i.e., annual average daily traffic), which is the number of vehicles at any given point (temporally and spatially) across the road network, was parsed at a 10-mile resolution across the network.
2. Vehicle count was summed within segments. VMT appropriate to the commercial vehicle classes was calculated by multiplying vehicle count by segment length for each segment. The result was aggregated to the 10-mile interval area. Because VMT calculated from HPMS data is liable to undercount actual VMT on the network, validation proceeded to scale up VMT to match statewide estimates for the relevant classes.
    - In order to transpose this vehicle activity across the United States to new ZE-MHDVs that will enter the market, a scaling factor for each segment was derived. This was calculated as *ZE-MHDV VMT in each segment/Total ZE-MHDV VMT across the United States*.
    - To determine the ZE-MHDV activity distribution across the United States, the total VMT based on sales estimates for single and combination ZE-MHDV was calculated. It was then multiplied by the scaling factor for each segment across the United States to derive the share of ZE-MHDV VMT at each segment.
3. Energy intensities were used to calculate the energy demand at each segment.
    - A population-based weighting factor was associated for deriving energy intensity for single vehicles composed of vehicles between Class 3 through 7.

This was calculated as 1.525 brake horsepower-hour per mile (bhp-hr/mile) for single vehicles and 0.94606 bhp-hr/mile for combination vehicles using MOVES factors and vehicle populations for corresponding vehicle weight classes. Energy demand per segment was then calculated by multiplying ZE-MHDV VMT per segment by the respective energy intensities.[7]

[7] While the above approach is applicable for calculating energy demand for all in-use vehicles on the corridor, in this study only the energy demand to cater to ZE-MHDVs that are expected to be electrified were of primary importance.

CALSTART's Drive to Zero program published expected zero-emission vehicle penetration pathways in various vehicle weight classes through 2050 (CALSTART, 2020b). This study used the 2030 and 2035 penetration percentages for single vehicles by summing the expected number of ZE-MHDVs in Classes 3–7 by 2030 and Class 8 ZE-MHDVs for combination vehicles. In this way, while ZE-MHDVs introduced across the United States are expected to be spatially dynamic and will appear depending on the phasing carried out, the total eventual distribution of ZE-MHDVs across the national surface transportation network ultimately is derived from the vehicle activity characteristics that constitute VMT distribution.

Deployment Prioritization

Having determined where vehicles would need to be introduced, the analysis then phased these areas by ranking their priority and determined deployment on the basis of that priority ranking. The timing and pace were validated against the timeline and pace of the original projected vehicle introduction.

The datasets associated with the priorities are listed above, but a summary of priorities and how they were weighted is below (Table A-4).

Table A-4. Priority Data

Category	Data	Weight
Identified investment areas	Industry investment areas (as identified spatial extents)	High
Identified investment areas	Federal investment areas	Medium
Political, social, equity priorities	State support for Global MOU	High
Political, social, equity priorities	State ACT adoption	High
Political, social, equity priorities	Statewide "high potential regions" identified by North American Council on Freight Efficiency and re-scored to include updated above political and social commitments	Low
Economic clustering	County NAICS code categories of "Transportation and Logistics," "Distribution and Electronic Commerce," and "Local Logistical Services"	Medium
Energy cost and grid improvement potential	NREL projected Levelized Cost of Energy data from 2020 to 2040 for solar and wind (commercial applications)	Low

The total scoring of the areas in terms of priority was developed by ranking each of the metrics for each area against the rest of the areas within the national network under consideration and normalizing them via min-max rescaling. They then were assigned due weights (of 1-5) and combined to produce a prioritization score. For example, Maricopa County, Arizona, scored nationally very high in terms of the share of solar and wind applications which would increase the potential that the distribution grid would be robust in the area. This was normalized and, after weighting, combined together with its ranks in terms of economic clustering and political and social priorities, as well as its priority as an identified investment area for industry or for the federal government. This calculation produced a composite score for Maricopa County.[8]

Phasing

From here, composite scores were cut into separate bins; the top ones, comprising one-third of areas, were considered Phase 1, the next half constituted Phase 2, and the remaining bins constituted Phase 3 (Table A-5).

Table A-5. Phase Definition

Type	Description
Phase 1	Begins currently; highest priority ranking areas; takes on percentage of future deployment
Phase 2	Begins 2027; middle ranking in terms of priority; takes on percentage of future deployment
Phase 3	Begins 2030; bottom ranking in terms of priority; shifted furthest back; does not take on percentage of future deployment

Finally, deployment was shifted to affect the phasing of buildout. Areas in Phase 1 would deploy starting presently through 2027, Phase 2 starting only after 2027. Both, however, could shift forward subsequent deployment to take on about 75 percent of its deployments, while areas within Phase 3 were shifted back in time to deploy 100 percent of their chargers between 2030 and 2035. In this way, a phasing of investment was carried out.

Following this step, validation of initial energy needs as forecasted against the phasing scenario was performed to ensure total deployment responded in a clear relationship to initial forecasts of energy demand.

Assumptions

Energy Needs Assumptions

The model involved several key assumptions:

- The vehicle activity data used from any week was representative of most weekly operations and adjusted for seasonality.

[8] Transformation of datasets at different resolutions was necessary. Where county-level data was necessary to transform to the more granular grid-level, county data once ranked was assigned equally to analysis grid areas within the county.

- Single vehicles were assumed to be comprised of vehicle Classes 3 through 7 and combination vehicles comprised of Class 8 vehicles.
- New ZE-MHDV introductions in the United States followed current vehicle activity/usage across the country.

These assumptions will be explored in future work.

Utilization Factors

Charging Power

The actual deployment of infrastructure was allowed flexibility with respect to what vehicles were required, reflecting two related tendencies assumed in other major studies and corroborated by industry experience: 1) operational considerations shift charger choices downward in many contexts for charging that would be overnight, but 2) the general trend for all charger selection is to increase utilization, yielding a continual preference for higher power charging through 2032. This was assumed to yield a shift from an initial distribution of chargers, which skews lower, toward Level 2 chargers and away from a larger share of higher power chargers to a U-shaped distribution in the charging power categories in deployment over the lifetime of this analysis. Table A-6 shows the assumed change in the share of chargers used by vehicle class through the study.

Table A-6. Deployment Distributions

Power Rating	Vehicle Class	Share of Chargers (present)	Share of Chargers (2032)
Level 2	Class 3-7	30 percent	30 percent
Level 2	Class 8	50 percent	10 percent
DCFC 50 kW	Class 3-7	30 percent	20 percent
DCFC 50 kW	Class 8	30 percent	10 percent
DCFC 150 kW	Class 3-7	30 percent	40 percent
DCFC 150 kW	Class 8	10 percent	20 percent
DCFC 350 kW	Class 3-7	10 percent	30 percent
DCFC 350 kW	Class 8	10 percent	60 percent

Sharing

Sharing in some form (by sharing a charger or an arrangement) was assumed to be prevalent within Phase 1 (hubs/clusters) at 75 percent of deployments and less prominent in other areas, where it was considered equally 50 percent of deployments.

Public Charging

Public charging was assumed to be prevalent within 30 percent of hub/cluster deployment areas, 50 percent of corridor deployment areas, and 90 percent of national network locations.

Costs

Unless otherwise indicated, costs were calculated per vehicle based on assumed costs derived from several sources (Table A-3).

Overall Costs

Overall costs were calculated after phasing of deployment and after validation of initial assessments of energy needs against deployment was performed. Costs presented in Table A-7 utilize the assumptions indicated in the following discussion.

Table A-7. Costs of Phased Scenario by Phase and Area ($ billions)

Area	Phase 1	Phase 2	Phase 3	Total
Cluster	$10.0	$37.2	$11.7	**$58.9**
Corridor	$1.9	$7.2	$5.6	**$14.7**
Network	-	$0.5	$5.2	**$5.7**
Total	**$11.9**	**$44.9**	**$22.5**	**$79.3**

The following were not factored into Table A-7: 1) incentives for public charging, which significantly reduce the upfront costs of deployment, and 2) federal and state investments in charging infrastructure, which will reduce the overall costs of deployment. Initial exploration of these costs, which will be developed in subsequent work, shows that the total costs can fall significantly with those two factors.

EVSE

For the purposes of this analysis, EVSE costs were derived from what EPA used per vehicle for its Proposed Phase 3 ruling (EPA 2023a; EPA 2023b). These assumptions were checked against academic studies on the subject and considered as a starting point for a baseline cost estimate (Muratori et al., 2021). CALSTART will, in future analyses, derive cost data from a wider array of both academic literature, industry data, and collected deployment data. A summary of costs per port (as per-vehicle) is below (Table A-8).

Table A-8. EVSE Base Costs

Power Rating	Costs per Port
Level 2	$10,541
DCFC 50 kW	$31,623
DCFC 150 kW	$99,066
DCFC 350 kW	$162,333

Assignment of Costs per Deployment

Costs were assigned to areas according to the distribution of chargers in different scenario phases (Table A-6).

Onsite Storage

Onsite storage costs were based on CALSTART internal data on project costs involving onsite storage. These were added to vehicle costs. Additional average costs per vehicle were estimated at a fraction of total charger cost based on industry data and project information available to CALSTART. This was determined based on data involving major deployments of onsite storage at nearly 600 kW with > 2-hour charge, to support deployments of 15 vehicles or more. Per-vehicle cost was calculated using cost estimations from NREL and Energy Information Administration (Table A-3) and added these as additional assumed costs to half of deployments of 150-kW chargers or higher.

Technology Diffusion

Analyses show that capital costs across energy delivery infrastructure have significant reductions due to technology learning rates, such as in solar technology. This analysis considered a technology reduction cost between 4 percent and 7 percent annually, similar to those historically seen over similar periods in wind and solar energy, as reasonable. These were applied to all deployments.