Colorado Electric Vehicle and Charging Needs Forecast

Technical Guidance Report

Prepared for:

Xcel Energy

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1. Introduction

Xcel Energy ("Company") engaged Guidehouse, Inc. ("Guidehouse") to assist in the preparation of its transportation electrification filings in Colorado. As part of this support, Guidehouse conducted a series of plug-in electric vehicle[1] ("PEV") modeling analyses leveraging its Vehicle Analytics & Simulation Tool ("VAST").

VAST is a systems dynamics model with two distinct modules that were executed in sequential order to support this engagement:

- **Vehicle Adoption:** This module forecasts adoption of various fuel and powertrain, ownership, and vehicle class configurations in each census tract in each jurisdiction. By modeling vehicle adoption based on inputs specific to a particular jurisdiction, the forecast closely reflects local market conditions providing a stronger empirical basis when compared to similar national, state, or regional forecasts.

- **Charging Needs:** This module forecasts charging infrastructure required to support the forecasted electric vehicle adoption, calculated through a dynamic market equilibrium model, i.e., the number of electric vehicle charging station (commonly referred to as "charger") ports required to supply a given number of vehicles.

Further details on VAST methodology are available in **Appendix A. VAST Vehicle Adoption Whitepaper** and **Appendix B. VAST Charging Needs Whitepaper**.

This memo presents an overview of Guidehouse's modeling methodology and associated results for:

1. **Vehicle Adoption** in the state of Colorado and Xcel Energy's Colorado service territory.
2. **Charging Needs** in the state of Colorado and Xcel Energy's Colorado service territory.

[1] Plug-in electric vehicle ("PEV") includes battery electric vehicles ("BEVs") and plug-in hybrid electric vehicles ("PHEVs").

2. Forecasting Background

2.1 Forecasting Approaches

Guidehouse provided two vehicle adoption forecasts for Public Service Company, Colorado ("PSCo") based on two different analytical approaches – a "goal seeking" approach and a "bottom-up market forecast" approach.

The vehicle adoption forecast Guidehouse used in the "Target 2030 Analysis" was built to result in electric vehicle adoption that meets Colorado's state target of 940,000 light-duty electric vehicles ("LDEV" or "electric LDV") on the road by 2030. This "goal seeking" approach to vehicle adoption forecasting was appropriate to assess the level of charging infrastructure required to support vehicle adoption commensurate with the state's target of 940,000 LDEVs by 2030. The intent of this analysis was to evaluate the charging needs associated with Colorado's adoption goal, not to model the precise conditions under which that level of LDEV adoption is likely to take place.

A separate analysis Guidehouse conducted in September 2022 addressed the question: "what level of electric vehicle adoption is expected in Colorado absent the state's 940,000 LDEV adoption goal in 2030?" The approach Guidehouse used to address this separate research question was not a "goal seeking forecast" (i.e., Target 2030 Analysis) but rather a "bottom-up market forecast," referred to herein as "Market Analysis." For further details on the Market Analysis, please see section **3.3 Vehicle Adoption Results – Market Analysis**.

Table 1 below summarizes the detailed VAST results included as appendices to this report. This report focuses primarily on the results of the Target 2030 Analysis.

Table 1. VAST Detailed Results Appendices

Region	Analysis	Approach	Appendix File Name
State	Vehicle Adoption	Target 2030	Appendix E - CO State_Vehicle Adoption_Target 2030.xlsx
State	Vehicle Adoption	Market	Appendix F - CO State_Vehicle Adoption_Market.xlsx
Service Territory	Vehicle Adoption	Target 2030	Appendix G - CO Territory_Vehicle Adoption_Target 2030.xlsx
Service Territory	Vehicle Adoption	Market	Appendix H - CO Territory_Vehicle Adoption_Market.xlsx
State	Charging Needs	Target 2030	Appendix I - CO State_Charging Needs_Target 2030.xlsx
Service Territory	Charging Needs	Target 2030	Appendix J - CO Territory_Charging Needs_Target 2030.xlsx

2.2 Goal Seeking Approach: Analysis Parameters

Analysis parameters are key model inputs that can be varied to simulate different market dynamics impacting vehicle adoption. These parameters include, but are not limited to, fuel prices, battery pack costs, incentives, customer awareness, powertrain preference, and vehicle availability. Parameter ranges are not inconsistent with the state objective, nor do they fall outside of major market trends as indicated by historical data, i.e., battery electric vehicle (“BEV”) and plug-in hybrid electric vehicle (“PHEV”) make and model availability.

All parameters in VAST default to "0" or null values before calibration. In order to achieve the goal of the Target 2030 analysis, parameter values were increased from zero to current (2022) values, and then beyond as necessary to achieve the goal of 940,000 Light Duty Electric Vehicles (LDEVs) on the road in Colorado by 2030. Colorado's current vehicle registration data[2] was used as the starting point (time step 0) in the goal seek.

For the Target 2030 Analysis, parameter values were changed, not based on prior or current empirical studies—as such analogs would be difficult or impossible to generate in a mathematically meaningful fashion—but rather to generate the pre-determined adoption levels required by the Colorado state target. No external studies were referenced for selecting the parameter values, consistent with the intent of a goal seeking exercise. Notably, Guidehouse took care to ensure the powertrain splits in 2030 were consistent with empirical adoption in Colorado according to the IHS Markit (S&P Global) data and OEM investment trajectories.

2.3 Policy Impacts: Inflation Reduction Act

The Inflation Reduction Act (“IRA”) of August 2022 directs federal spending towards US innovation, including upgrades to US infrastructure and clean energy. It reforms energy tax incentives through a mix of modifications, extensions, and new programs, including those for EVs. Impacts of these policy changes include:

- Removal of 200,000 vehicles per OEM cap on tax credit
- Availability of credits to 2032 up to $7,500 for light truck BEVs regardless of OEM
- Limits on incentive applicability based on price
- Limit of credit to income-eligible households
- North America materials and assembly requirements
- New incentives for medium- and heavy-duty EVs, covering incremental cost over diesel/ gasoline alternative
- New infrastructure tax credits (up to $100,000 per qualified alternative fuel vehicle refueling property)
- Addition of $4,000 tax credits for used vehicles

Modules within VAST incorporate these policy additions by applying changes to tax incentives and other drivers of total cost of ownership (“TCO”). See **Appendix A. VAST Vehicle Adoption Whitepaper** for more information.

[2] IHS Markit (as of Q4 2021)

3. Vehicle Adoption Modeling

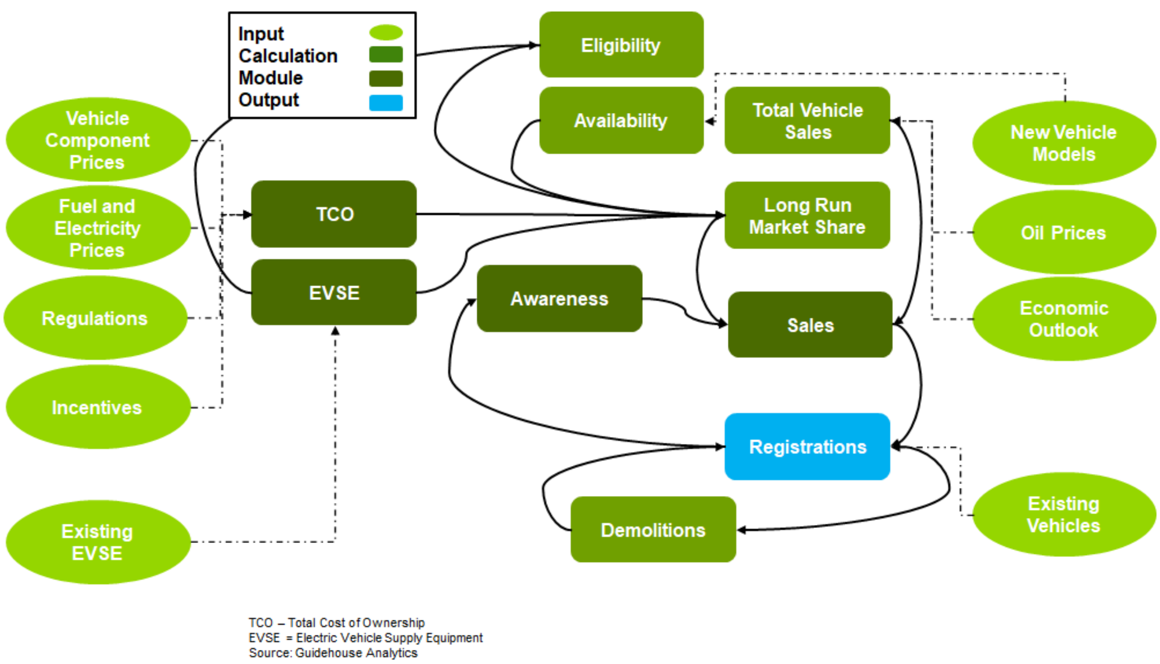
Guidehouse's VAST uses a systems dynamics model[3] driven by enhanced Bass diffusion[4], conditioned on vehicle availability, customer ownership economics, and eligibility constraints. This means that the fundamental cause and effect relationships in the system are defined and calibrated.

3.1 Vehicle Adoption Methodology Summary

The VAST Vehicle Adoption module explicitly accounts for supply-side dynamics driving vehicle production and availability as new models are rolled out preferentially to specific geographies in response to specific markets or policy drivers. If a vehicle is available, the economics of vehicle ownership, customer decision-making, and the impact of word-of-mouth effects and advertising all affect vehicle sales. This formulation is more accurate than strict autoregressive time-series forecast models, like generalized autoregressive conditional heteroskedasticity ("GARCH") or autoregressive integrated moving average ("ARIMA") models and outperforms econometric models because the system is fundamentally bounded by stocks and flows and can account for non-linear dynamics that arise from positive and negative feedback, balancing effects, and reinforcing trends.

Figure 1 depicts a high-level diagram explaining the relationships between the major model routines.

Figure 1. VAST Vehicle Adoption Methodology



Source: Guidehouse

[3] Sterman, John D. Business Dynamics: Systems Thinking and Modeling for a Complex World. Irwin McGraw-Hill. 2000.

[4] Bass, Frank (1969). "A new product growth model for consumer durables." Management Science 15 (5): p 215-227.

3.2 Vehicle Adoption Results – Target 2030 Analysis

In Colorado, Guidehouse modeled vehicle adoption for the Target 2030 Analysis to align with the state target of 940,000 LDEVs by 2030. This analysis resulted in a total of 939,790 LDEVs in the state and 540,065 LDEVs in the PSCo service territory by 2030. This analysis models lower market share for electric medium- and heavy-duty vehicles ("MDV" and "HDV"), primarily due to limitations in model availability. **Table 2** and **Table 3** below summarize the Target 2030 Analysis forecasted electric vehicle (BEV and PHEV) adoption results for the PSCo service territory and for the state of Colorado respectively.

Table 2. Target 2030 Analysis – PSCo Vehicle Adoption Results

Vehicles	2022	2026	2030
Electric LDVs (#)	59,410	249,464	540,065
Electric MDVs (#)	177	1,210	2,689
Electric HDVs (#)	139	701	1,532
Electric LDVs (% of All LDVs)	2%	8%	15%
Electric MDVs (% of All MDVs)	0%	2%	3%
Electric HDVs (% of All HDVs)	0%	2%	4%

Source: Guidehouse

Table 3. Target 2030 Analysis – Colorado Statewide Vehicle Adoption Results

Vehicles	2022	2026	2030
Electric LDVs (#)	99,466	426,220	939,790
Electric MDVs (#)	415	2,939	6,607
Electric HDVs (#)	277	1,617	3,639
Electric LDVs (% of All LDVs)	2%	7%	14%
Electric MDVs (% of All MDVs)	0%	1%	3%
Electric HDVs (% of All HDVs)	0%	2%	3%

Source: Guidehouse

3.3 Vehicle Adoption Results – Market Analysis

The Target 2030 Analysis discussed above was developed to result in electric vehicle adoption that meets Colorado's state target of 940,000 LDEVs on the road by 2030. Separately, Guidehouse conducted a distinct market analysis in September 2022 to forecast the electric vehicle adoption expected in Colorado, based on market conditions at the time of analysis, i.e., notwithstanding the state's goal of 940,000 LDEV on the road in 2030. The Market Forecast *does not* represent a baseline, but rather is a separate bottom-up analysis with independent assumptions. For further details on the differences between these analyses, please see section **2. Forecasting Background**.

Notably, in addition to not taking a "goal seeking" forecasting approach or incorporating the 2030 Colorado state target, the Market Analysis is:

- Provided in the interest of transparency to support stakeholder awareness of the difference between Guidehouse's approach to a "goal seeking forecast" versus a "bottom-up market forecast."
- Not a baseline or "business as usual" case for the Target 2030 Analysis (there was no baseline for this "goal seeking forecast" consistent with the purpose of a goal-seeking exercise).
- Not reflective of changes in key market dynamics or interventions since September 2022, including but not limited to, Bipartisan Infrastructure Law provisions, fuel prices, battery pack prices, consumer awareness, vehicle availability, and other key parameters modeled in VAST.
- Not recommended by Guidehouse or Xcel Energy for use by any entity for business or policy decision making as it is an outdated forecast and not reflective of significant market changes since September 2022.

The Market Analysis resulted in a total of 758,493 LDEVs in the state and 435,057 LDEVs in the PSCo service territory by 2030, with high adoption concentrated in metro areas of the PSCo territory such as Denver, Boulder, and Fort Collins. The forecasted level of statewide LDEV adoption in the Market Analysis achieves only 81% of the 940,000 LDEV state target in 2030, translating to roughly 11% market share of the forecasted LDV population in the state. **Table 4** and

Table 5 below summarize the Market Analysis forecasted electric vehicle adoption results for the PSCo service territory and for the state of Colorado respectively.

Table 4. Market Analysis – PSCo Vehicle Adoption Results[5]

Vehicles	2022	2026	2030
Electric LDVs (#)	50,500	188,785	435,056
Electric MDVs (#)	177	1,210	2,689
Electric HDVs (#)	139	701	1,532

[5] Electric MDV and HDV forecasts are consistent between the Market Analysis and the Target 2030 Analysis, as the Target 2030 Analysis was modeled to reach the state's target of 940,000 LDEV by 2030.

Vehicles	2022	2026	2030
Electric LDVs (% of All LDVs)	2%	6%	12%
Electric MDVs (% of All MDVs)	0%	2%	3%
Electric HDVs (% of All HDVs)	0%	2%	4%

Source: Guidehouse

Table 5. Market Analysis – Colorado Statewide Vehicle Adoption Results

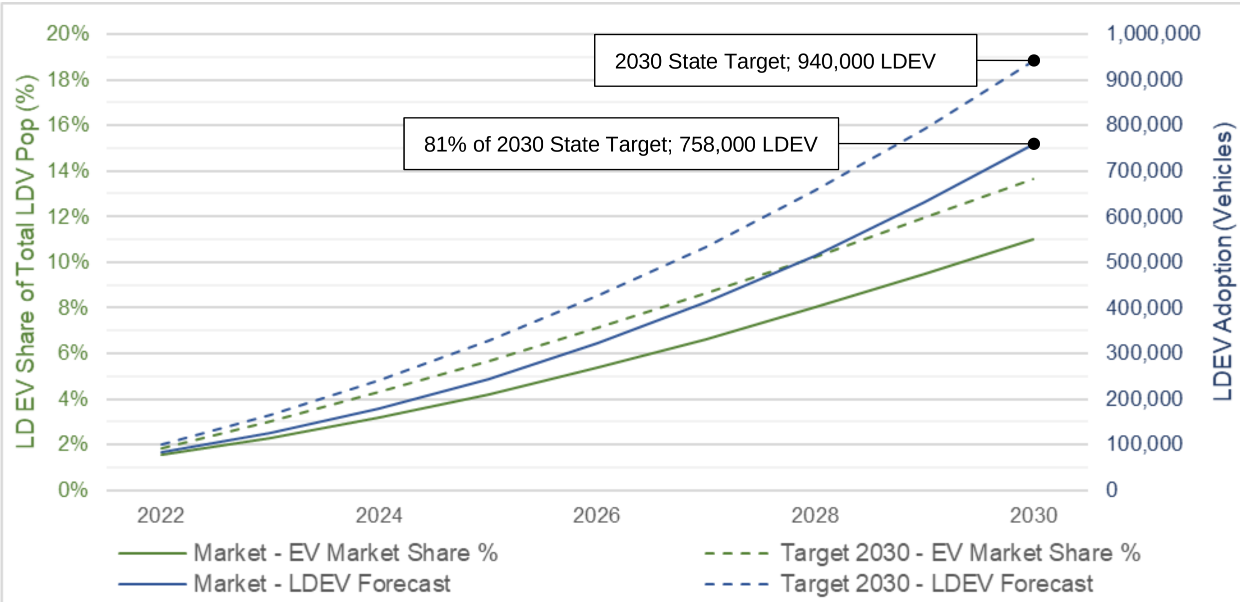
Vehicles	2022	2026	2030
Electric LDVs (#)	84,459	322,683	758,493
Electric MDVs (#)	415	2,939	6,607
Electric HDVs (#)	277	1,617	3,639
Electric LDVs (% of All LDVs)	2%	5%	11%
Electric MDVs (% of All MDVs)	0%	1%	3%
Electric HDVs (% of All HDVs)	0%	2%	3%

Source: Guidehouse

Figure 2 and

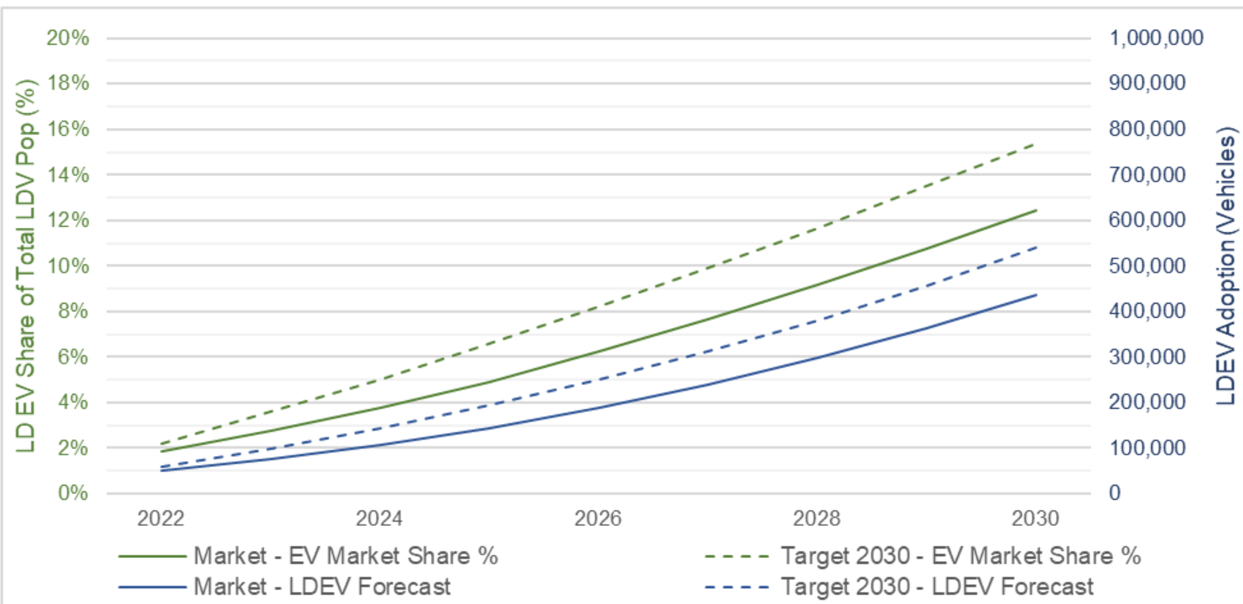
Figure 3 illustrate the differences in vehicle adoption between the Market Analysis and the Target 2030 Analysis, for the state and PSCo service territory respectively. As can be seen in **Figure 2**, the Target 2030 Analysis was modeled to align with the state target of 940,000 LDEVs in the state by 2030, while the Market Analysis falls short of this goal (81% of 2030 target).

Figure 2. CO State EV Adoption Results



Source: Guidehouse

Figure 3. PSCo Service Territory EV Adoption Results



Source: Guidehouse

4. Charging Needs Modeling

4.1 Charging Needs Methodology Summary

The VAST Charging Needs module takes changes in the vehicle population associated with a specific fuel drive infrastructure build-out as an input. For example, as electric vehicle supply equipment ("EVSE") rollouts continue, the portion of the market that can consider purchasing a PEV increases and the economic disadvantage of PEV ownership decreases because PEVs can meet more consumer transportation needs. Economic disadvantage is formulated to reflect the vehicle's ability to satisfy all the driving requirements of its owner and is consequently modeled as a cost added to the TCO[6]. Guidehouse refers to this cost as the consumer sacrifice penalty.

Fueling infrastructure and vehicle populations evolve together in VAST. The Charging Needs forecast simulates the transition from the existing charging network to a market equilibrium network. As such it is assumed that adequate charging infrastructure will be built out to serve the electric vehicles on the road. More vehicles on the road with specific fuel requirements dictated by the powertrain stimulate infrastructure development for the relevant fuel. This is accomplished through the estimation of dynamic regional charger-per-vehicle ratios[7]. They are regional, reflecting local traffic and driving patterns, and dynamic, reflecting changing technology, range, and use case preferences among drivers. Charging levels (rated capacity) evolve over time in the model in response to vehicle range, penetration, and use case requirements.

The public charging requirements included in Guidehouse's charging needs assessment include publicly accessible charging stations (i.e., accessible to all EV drivers) and existing semi-private, or proprietary charging stations (i.e., charging stations available only to certain EV drivers, such as Tesla or Rivian networks). Guidehouse's model discounts the port counts of these proprietary networks proportionately to account for the lack of accessibility to all drivers.

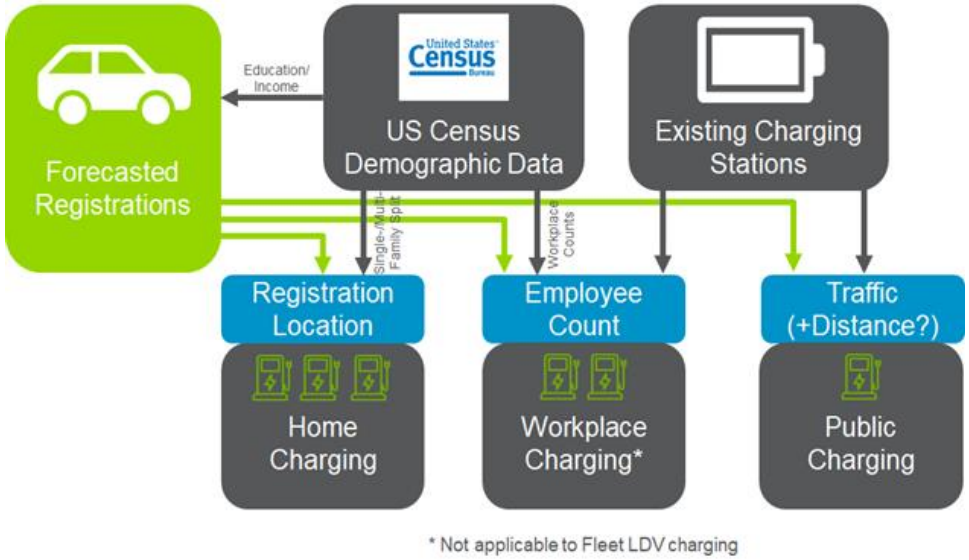
The Charging Needs methodology's handling of the Tesla Supercharger network illustrates this discounting. Guidehouse discounted the Tesla charging network in the sense that Tesla's private network was only counted in proportion to the number of registered Tesla vehicles on the road. This was done to account for the fact that the proprietary Tesla network does not provide connectivity to non-Tesla vehicles. Thus, the analysis fully accounts for the market share that Tesla currently holds in Colorado, both in terms of the vehicles and the charging network, and implicitly assumes that this share stays the same over time. The analysis does not make specific assumptions about future Tesla charging network build-out in the state.

Figure 4 illustrates the VAST methodology for connecting charging stations with vehicle registrations.

[6] There is no assumed infrastructure penalty associated with PHEVs, due to PHEVs ability to use gas and avoid the need for rental cars on long trips.

[7] The term "charger" in this context refers to plug-in electric vehicle charging station ports.

Figure 4. VAST Charging Needs Methodology



Source: Guidehouse

4.2 Charging Needs Results – Target 2030 Analysis

Guidehouse developed an infrastructure forecast as part of the CO Target 2030 Analysis for the PSCo service territory. This infrastructure forecast was conducted both at the state and service territory levels in order to quantify the required infrastructure at both geographic levels. This forecast provides the equilibrium number of charging ports required to support forecasted electric transportation needs. For more information, please see section **4.1 Charging Needs Methodology Summary** above and **Appendix B. VAST Charging Needs Whitepaper**.

Guidehouse's projections for infrastructure requirements show that by 2030, over 20,500 Level 2 ("L2") ports and 6,000 direct current fast charge ("DCFC") ports will be required to support public charging for PEVs adopted in PSCo territory. Full results for infrastructure projections can be found in **Table 6**, which is inclusive of existing charging infrastructure available today.

Table 6. Target 2030 Analysis – PSCo Charging Needs Results

	2022	2026	2030
Public Level 2 Charging (MW)	33	155	292
Public Level 2 Charging (Ports)	4,725	14,571	20,585
Public DCFC Charging (MW)	61	497	1403
Public DCFC Charging (Ports)	911	3,521	6,313

Source: Guidehouse

4.3 Adoption & Charging Needs Modeling Insights

Future vehicle adoption and charging needs are driven by many market factors. Consideration of these factors is essential in developing robust and reliable forecasts. **Table 7** lists key factors incorporated in Guidehouse's vehicle adoption and charging needs forecasts.

Table 7. VAST Adoption and Charging Needs Factors

Adoption and Charging Needs Factor	Description
Regulatory Targets	Future PEV penetration targets established by regulatory bodies or government agencies
Awareness	Consumer's knowledge of the PEV market
Availability	Ability of the PEV market to meet the specific demand of a consumer, e.g., if a consumer wants an electric minivan a suitable product is commercially available for purchase
Customer Preference	Inherent non-economic drivers of customer powertrain purchase behavior such as perceived vehicle performance, style, and attractiveness
Total Cost of Ownership	The total cost to a consumer who purchases a PEV, incorporating capital expenses, operating expenses, and existing incentives
Charger-to-Vehicle Ratio	The measurement of how much charging infrastructure is required to meet the charging demand generated by PEV adoption

Source: Guidehouse

In the Colorado National Electric Vehicle Infrastructure ("NEVI") Plan, the State established ambitious targets for transportation electrification to closely align with the NEVI Formula Program vision and goals. The State's most recent plan established a light-duty vehicle target of 940,000 EVs on the road by 2030.[8] While the state vehicle target was specific enough for Guidehouse to include in the Vehicle Adoption module for the Target 2023 Analysis, the data on NEVI charging stations were under development at the time of the analysis, and therefore were not included in the Charging Needs module.

In Guidehouse's view, achieving this light-duty vehicle target in Colorado requires market conditions that favor PEV adoption. Key market conditions include:

- Federal- and state-level market interventions will be needed to maximize awareness, such as those contemplated in the recent Build Back Better Agenda tax incentives for PEV purchase
- Availability of PEVs will need to develop significantly with no supply chain constraints
- Production of internal combustion engine ("ICE") vehicles will need to be commensurately reduced or banned; an approach Guidehouse applies to forecasts in California where ICE vehicles will be banned by 2035

[8] Colorado National Electric Vehicle Infrastructure ("NEVI") Plan, July 2022 Colorado Department of Transportation.

- Customer preferences of PEV performance must consistently be viewed a favorable over ICE vehicle

Understanding the charging needs associated with increased PEV adoption is essential to inform effective and efficient charging site deployments to support and unlock PEV market demand. Charger-to-vehicle ratios must take into consideration developing charging behavior in EV owners, such as shifts from home charging to public market charging as public charging stations become more available and as EV adoption increases beyond detached households with dedicated charging solutions. The evolution of technology, such as availability and affordability of DCFC charging stations and improved rated capacity on L2 and DCFC charging stations, will further define the capacity required to support the PEV market.

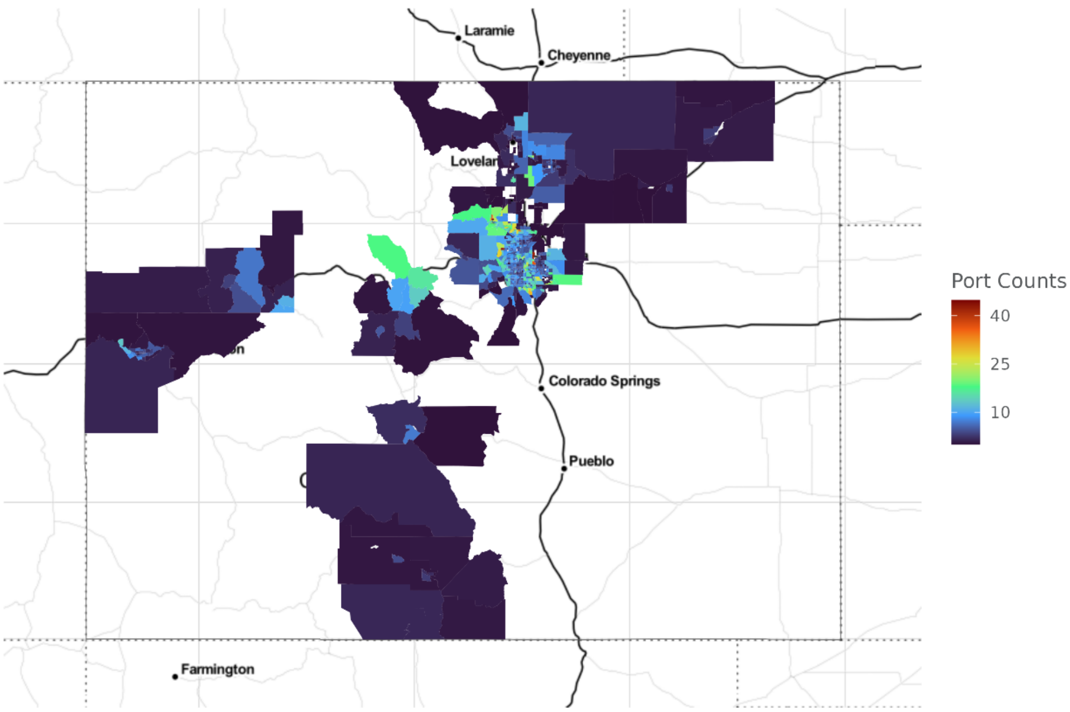
As the PEV market is still nascent, the inclusion of many factors is essential to support robust, reliable modeling. These factors will continue to develop in parallel with the PEV market and it is important to revisit and refresh underlying assumptions as increasingly reliable and relevant information becomes available.

5. Comparing Available Charging to Target 2030 Analysis Charging Needs

The difference between currently available charging infrastructure and the Target 2030 Analysis Charging Needs forecast can be visualized as a choropleth ("heat map") to illustrate geographic differences in charging needs and highlight locations where the greatest differences, or intensities, in charging needs could exist.

To illustrate these charging need intensities, **Figure 5** depicts the difference between currently available charging infrastructure, as reported by the Department of Energy's Alternative Fuels Data Center ("AFDC"), and the Target 2030 Analysis in terms of DCFC public charging port counts for census tracts in the PSCO territory in 2030. Note, PSCo service territory bounds do not follow census tract lines, so not all portions of each tract shown below fall within the PSCo service territory.

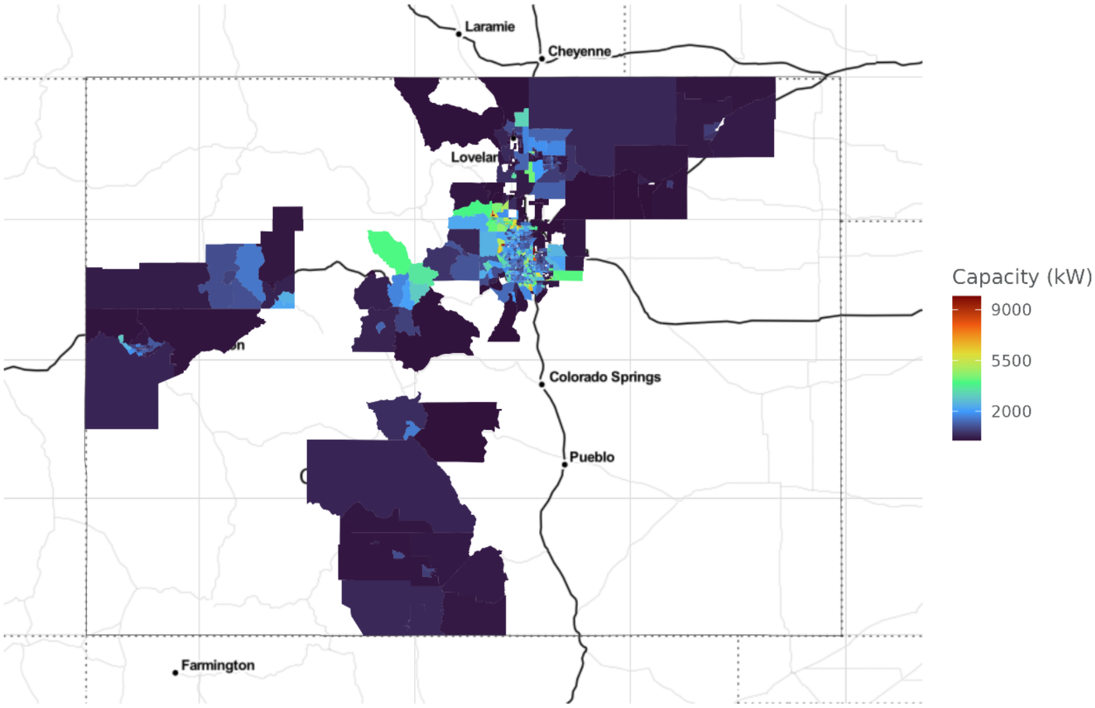
Figure 5. PSCo Charging Needs Port Count Intensity Heat Map 2030



Source: Guidehouse

To further illustrate the charging need intensities, **Figure 6** depicts the difference between currently available charging infrastructure and the Target 2030 Analysis Charging Needs in terms of DCFC public charging capacity.

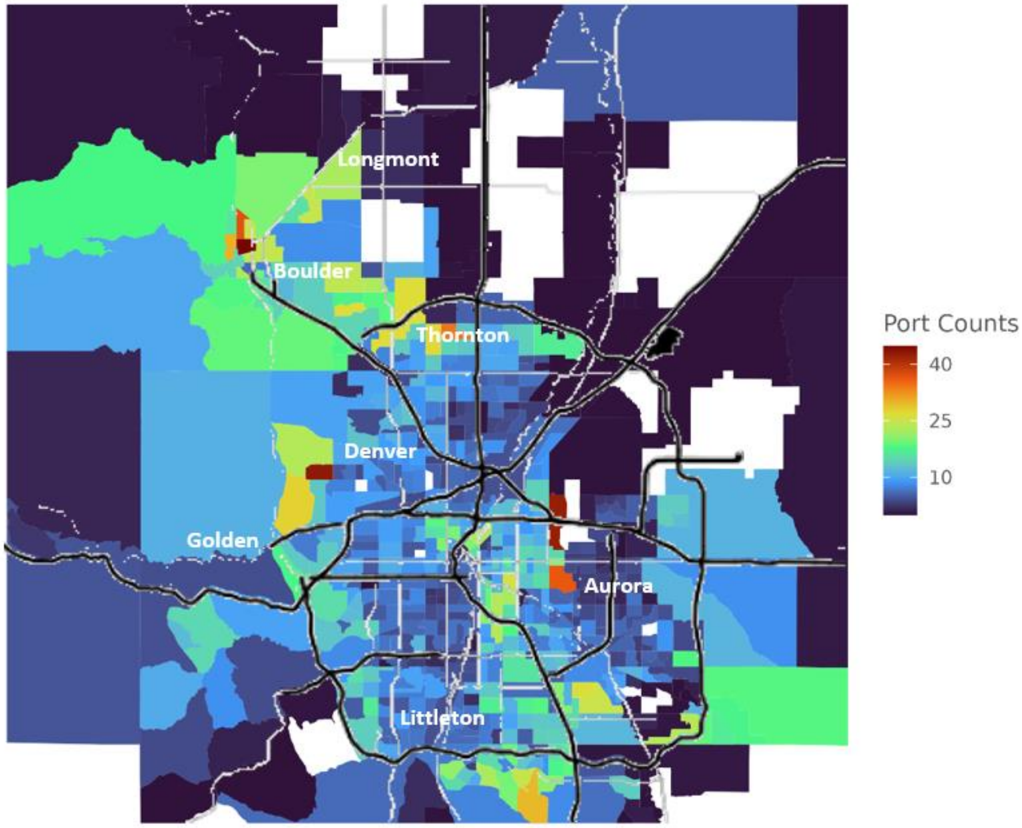
Figure 6. PSCo Charging Needs Capacity Intensity Heat Map 2030



Source: Guidehouse

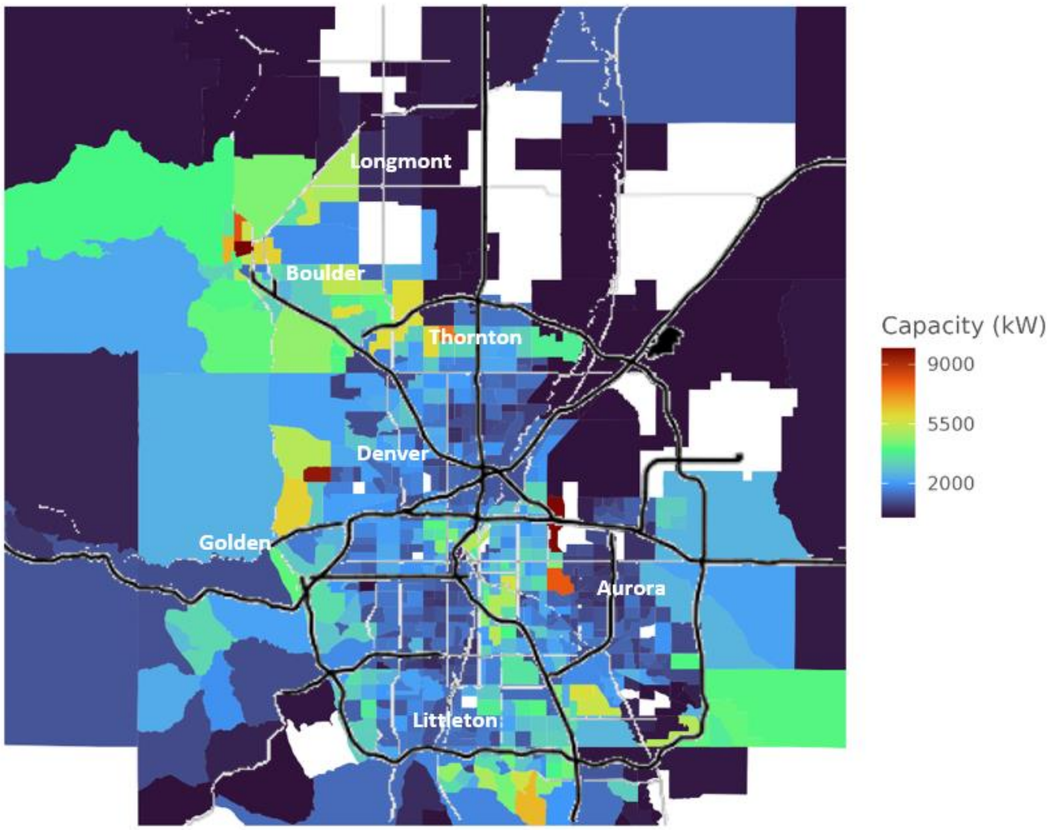
Public charging need correlates strongly with population and traffic density, as illustrated by the higher capacity and port count intensities surrounding the Denver metropolitan area, including Boulder, Golden, and Longmont, reflected by the brightly colored clusters in the figures below. **Figure 7** and **Figure 8** include zoomed-in images of the port count and capacity intensities respectively for the Denver metropolitan area to emphasize these differences. Guidehouse forecasts significantly higher public DCFC charging need in these areas in the Target 2030 Analysis, where the state's 2030 target of 940,000 LDEVs is met, than is currently available.

Figure 7. Denver Metropolitan Area Port Count Intensity Heat Map 2030



Source: Guidehouse

Figure 8. Denver Metropolitan Area Capacity Intensity Heat Map 2030



Source: Guidehouse

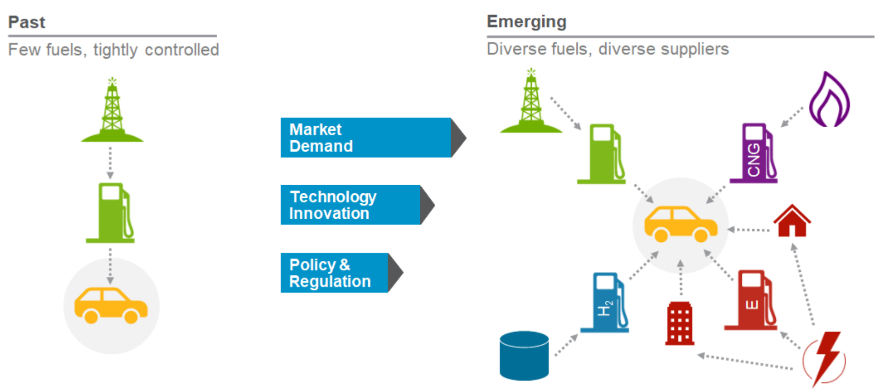
Appendix A. VAST Vehicle Adoption Whitepaper

A.1 Introduction

The automotive industry is evolving. The next decade should see increased global adoption of plug-in electric vehicles ("PEVs" or "EVs") across multiple vehicle classes and use cases and the anticipated commercialization of automated vehicles ("AVs," also known as self-driving vehicles). The change is amplified by federal and local policies and a large shift in investment by original equipment manufacturers ("OEMs").[9] These disruptions mark the early stages of a long development cycle, such that the technologies available today will change significantly as these market trends converge and mature. The magnitude and speed of this evolution hinges on global market forces, including government policies occurring outside of local jurisdictions.

By 2050, the electric powertrain vehicles forecast today are likely to look, operate, and serve functional use cases very different from the vehicle population today. This has significant implications for the results presented in any PEV analysis today. Guidehouse is working with clients throughout the transportation electrification ecosystem to address the difficulty of planning around and through this evolution. This white paper describes how we combine industry-leading thinking and modeling to provide in-depth insights into how changes to future transportation system fuels and modes (as **Figure 9** depicts) will impact PEV adoption.

Figure 9. The Shift in Transportation Fuels



Source: Guidehouse

A.2 Model Dynamics

Guidehouse's Vehicle Analytics & Simulation Tool ("VAST") Adoption module uses a systems dynamics framework to forecast adoption of various powertrain-fuel and vehicle class configurations in the PEV[10] market at the census tract-level. By modeling vehicle adoption based on inputs specific to a particular jurisdiction, the forecast closely reflects local market conditions compared to similar national-, state-, or territory-level forecasts. Guidehouse uses a calibrated enhanced Bass diffusion model to forecast new vehicle sales split between

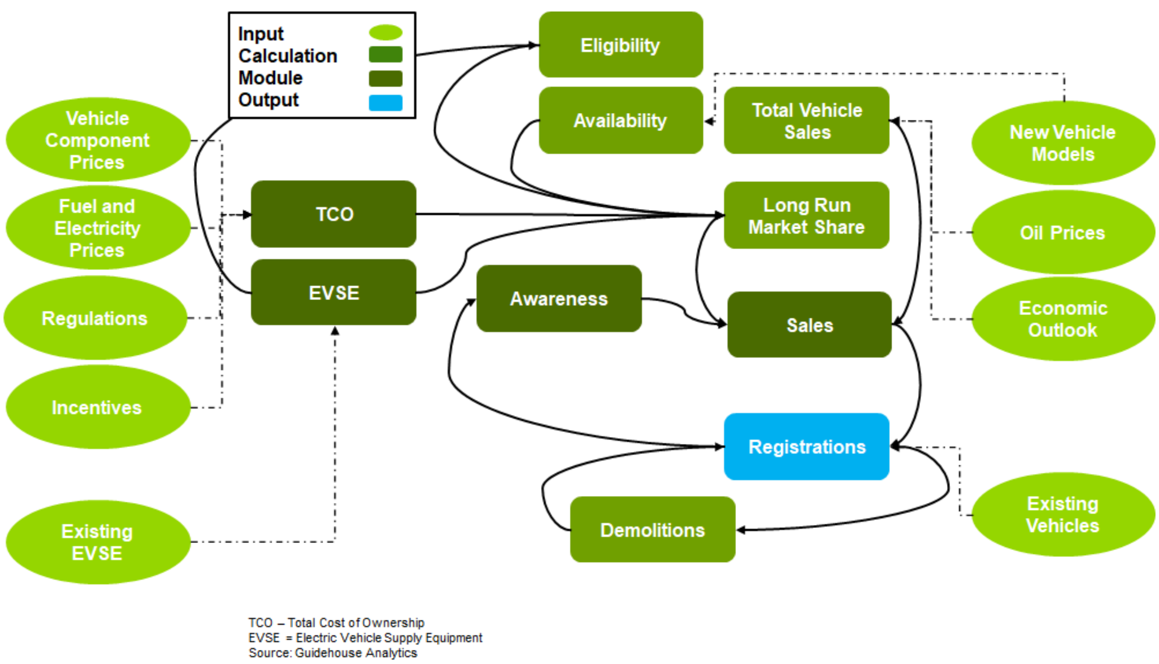
[9] **https://www.reuters.com/technology/exclusive-automakers-double-spending-evs-batteries-12-trillion-by-2030-2022-10-21/**

[10] PEV includes plug-in hybrid EVs, which include combined internal combustion engine and battery-based powertrains, as well as battery EVs, that only contain battery powertrains.

competing powertrains and vehicle classes and fits the parameters of this model to nine years of historical localized data.

VAST is a systems dynamics model[11] driven by enhanced Bass diffusion,[12] conditioned on vehicle availability, customer ownership economics, and eligibility constraints. This means that the fundamental cause and effect relationships in the system are defined and calibrated. For example, the model explicitly accounts for supply-side dynamics driving vehicle production and availability as new models are rolled out preferentially to specific geographies in response to specific markets or policy drivers. If a vehicle is available, the economics of vehicle ownership, customer decision-making, and the impact of word-of-mouth effects and advertising all affect vehicle sales. Similarly, the feedback between electric vehicle supply equipment ("EVSE") and vehicles on the road can be modeled directly. This formulation is more accurate than strict autoregressive time-series forecast models like generalized autoregressive conditional heteroskedasticity ("GARCH") or autoregressive integrated moving average ("ARIMA") models and outperforms econometric models because the system is fundamentally bounded by stocks and flows and can account for non-linear dynamics that arise from positive and negative feedback, balancing effects, and reinforcing trends. **Figure 10** depicts a high-level diagram explaining the relationships between the major model routines.

Figure 10. VAST Systems Dynamics Innovation Diffusion Approach



Source: Guidehouse

A.2.1 Total Vehicle Sales

Before estimating splits between powertrains, VAST forecasts the trajectory of vehicle sales by class, duty, country, and state. The model first establishes statistical relationships between historical vehicle sales and predictors such as population, active businesses, unemployment,

[11] Sterman, John D., "Business Dynamics: Systems Thinking and Modeling for a Complex World," Irwin McGraw-Hill. 2000.

[12] Bass, Frank (1969), "A New Product Growth Model for Consumer Durables," *Management Science 15 (5): p 215-227.*

and GDP. Then, VAST uses separate ARIMA models trained on historical data to create a forecast of each variable, for each model dimension (state, country, duty). Guidehouse then combines forecasts algorithmically, allowing prediction of best-guess total market sales and margins of error. These are passed into the adoption model as the “Total Vehicle Sales” variable in **Figure 10**.

A.2.2 Long-Run Market Share: Competition Between Powertrains

Enhanced Bass diffusion models dynamically update the asymptote of the Bass diffusion equation. The dynamic asymptote is known as the long-run market share. The long-run market share is calculated in a multinomial logit formulation,[13] where each powertrain within a vehicle duty, class, and ownership category competes for market share. It can be thought of as determining the split between different fuel options in the market, assuming complete awareness of all technology options.

Equation 1 below illustrates the market share *P* split for each technology *i* with attribute *j.* Technologies in this case are the powertrain and duty-class combinations – for example light-duty battery electric vehicles (“BEVs”) or medium-duty hybrid fuel cell vehicles (“HFCV”).

Equation 1

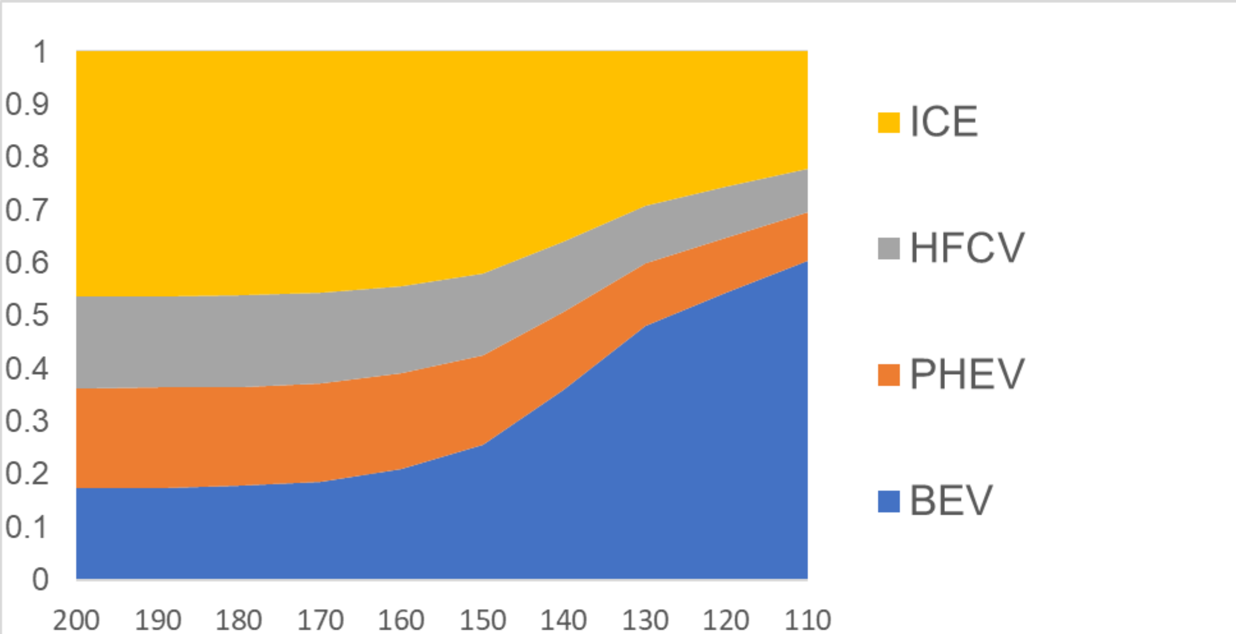
$$P_{i1} = \frac{exp\ (U_{i1})}{exp(U_{i0})\ + exp(\ U_{i1})}$$

$$U_{i1} = B0_i + \ B_{ij} * X_j + E_{ij}$$

This formulation allows for the model to account for a mix of time-variant economic attributes such as operating expenditures (“OpEx”) and capital expenditures (“CapEX”) and incentives contributing to the TCO alongside non-economic attributes like performance and customer preference by quantification of these attributes (*X*), and the coefficients (*B*) on them. **Figure 11** illustrates how the decrease in BEV TCO along the x-axis increases the market share for BEV in the y-axis when holding all other factors constant. Importantly, the gain in market share for one technology necessitates a loss in market share for another technology.

[13] McFadden, Daniel, and Kenneth Train. "Mixed MNL models for discrete response." *Journal of applied Econometrics* 15, no. 5 (2000): 447-470.

Figure 11. Logit Market Share Illustration



Source: Guidehouse

The model determines PEV sales by multiplying PEV market share by the overall eligible vehicle sales market, including internal combustion engine ("ICE") vehicles, and the percentage of customers that are fully aware (enough to make an informed economic purchase decision) of the PEV (including PHEV and BEV) or HFCV options. We develop vehicle stocks, also known as vehicle registrations or vehicle populations, by cumulating vehicle sales, less annual scrappage.

A.2.3 Fueling Infrastructure and Vehicle Adoption

An important component of the model architecture is the relationship between refueling infrastructure and vehicle sales. The model assumes infrastructure build-out is driven by changes in the vehicle population consuming a specific fuel. For example, as EV supply equipment rollouts continue, the portion of the market that can consider purchasing a PEV increases and the economic disadvantage of PEV ownership decreases because PEVs can meet more consumer transportation needs. Economic disadvantage is formulated to reflect the vehicle's ability to satisfy all the driving requirements of its owner and is consequently modeled as a cost added to the TCO.[14] Guidehouse refers to this cost as the consumer sacrifice penalty.

A.2.4 The Vehicle Sales Forecast and Model Calibration

Awareness evolves over time, according to the Bass diffusion process, given calibrated word-of-mouth and marketing strength parameters *(p* and *q* terms in the Bass Diffusion equation*)*. The

[14] There is no assumed infrastructure penalty associated with PHEVs, due to PHEVs ability to use gas and avoid the need for rental cars on long trips.

PEV population is then calculated as cumulative new vehicle sales minus vehicle retirements, which are a function of assumptions about average vehicle life.[15]

The Bass diffusion process can be generalized as follows in **Equation 2**.

Equation 2

$$\frac{\frac{d}{dt}A(t)}{1-A(t)} = p + qA(t)$$

Where *t* is the time in question, *p* is the marketing coefficient, *q* is the word-of-mouth coefficient, and *A* is the number of adopters expressed as a fraction of the applicable market. New vehicle sales (*s)* for each powertrain are expressed in **Equation 3** where *m* is the max market potential, defined as the market share multiplied by the relevant constrained vehicle stocks.

Equation 3

$$s(t) = m\frac{(p+q)^2}{p} * \frac{e^{-(p+q)t}}{\left(1+\frac{q}{p}e^{-(p+q)t}\right)^2}$$

The calibration process enables the forecast to have a strong empirical basis and grounds in the market realities of each state or province for each category of vehicle. In model calibration, the vehicle sales simulation is run over a historical period for which empirical vehicle sales and registration data is available, for example, 2011 to 2020. The Bass diffusion parameters representing word-of-mouth effects and advertising effects are fit to this historic data using a modified gradient descent Monte Carlo process. The goal of the calibration routine is to lessen the root mean squared error between the simulated vehicle sales and the actual observed vehicle sales over the same period for each state or province, class, duty, powertrain, and ownership combination within VAST. By fitting the model using observed vehicle sales and registration data in a formal back-cast process, Guidehouse ensures that the forecast provides an accurate simulation of each market segment.

A.2.5 Stocks and Supply-Side Modeling

One of the advantages of structural modeling is the ability to explicitly model each component of a complex system.[16] This is critical when the components of the system interact. In the case of electric vehicles, the demand side (modeled by the enhanced Bass Diffusion framework described above) is constrained by the supply side: the actions of OEMs that result in vehicles being advertised, released, and made available to the public. VAST models new vehicle releases through a dynamic called “Availability”, and the production of these vehicles through a dynamic called “Production Capacity”. The availability model draws data in through registrations and OEM press releases to simulate the release of new make/model combinations into a vehicle sub class (for example, luxury sedans). Just as the make/model combinations roll up to sub-classes, the sub-classes roll up into an overall class availability fraction, which is appropriately weighted. Thus, the release of a new BEV two seat sports car will not affect the simulated availability of light duty trucks, and no new release of a model into a vehicle subclass

[15] The model assumes all vehicles sold in a given jurisdiction remain in the jurisdiction and does not consider used vehicle sales.

[16] Sterman, John. *Business dynamics*. Irwin/McGraw-Hill c2000.., 2010.

that is already available will impact availability. Production capacity is conditional on availability, but modeled independently, to capture the time required to scale up production and delivery of a new vehicle model or platform to dealers and customers. A new model thus may be available in the market, but only produced in a very limited number. This constrains the applicable stocks.

A.2.6 Geographic Specificity

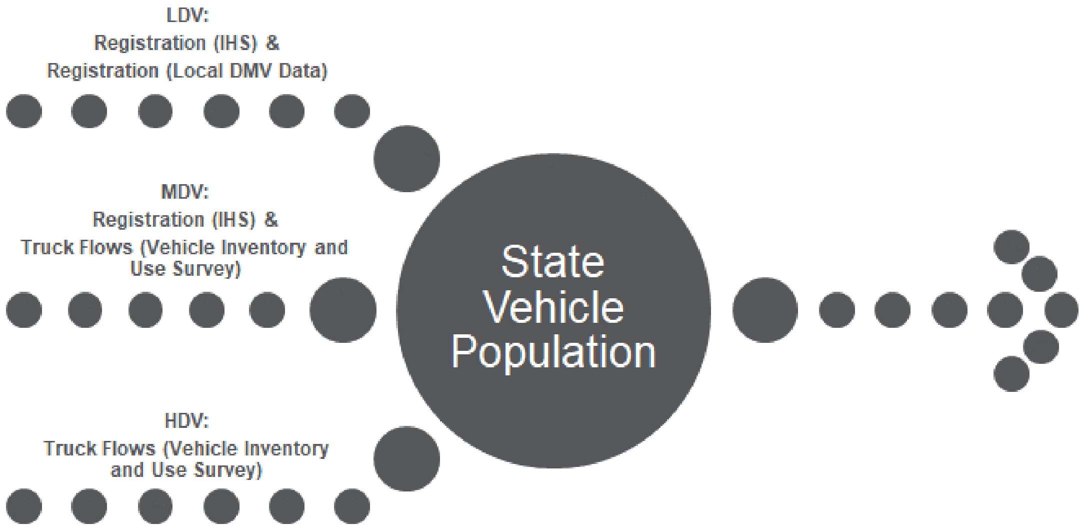
Geographically refined adoption (e.g., county, ZIP code, or census tract) is calculated by developing specific trajectories, initial conditions, and asymptotes for each geographic location. These are determined in a bottom-up sub-module that creates separate adoption curves using demographic variables such as income, education, and population, vehicle registrations, and population growth estimates. In a simplified view, population determines the asymptote, demographics determine the trajectory, and PEV registrations in the base year determine the initial conditions. Two theoretical ZIP codes might have the same total population and demographics and so would have identical curves describing how PEVs would diffuse over time. If they were otherwise identical but one had a higher initial adopter population, then that ZIP code would start higher on the curve relative to its twin. By default, variables are passed as an independent index, such that each geography will be affected similarly by rebate offerings, for example. The actual adoption numbers are conditioned on the territory- or state-level forecast to ensure that the state-level model can be aligned with the bottom-up geographic model.

A.3 Light, Medium, and Heavy-Duty Vehicle Methodology

Guidehouse’s VAST model forecasts adoption of various powertrain fuel configurations in the light duty vehicle (“LDV”), medium duty vehicle (“MDV”), and heavy-duty vehicle (“HDV”) markets. LDV classes include passenger cars and light trucks. MDV classes include delivery trucks and school buses, and HDV classes include semi-trucks and transit buses.[17] All classes are forecast and indexed by ownership—individual and fleet. **Figure 12** depicts how the VAST model analysis outputs contribute to estimating state-level vehicle populations. Since MDV and HDV (“MHDV”) penetration is extremely low for many areas, where needed, the calibration routine in VAST will learn from the historic rate of adoption of fleet LDVs to train the Bass diffusion parameters for medium and heavy-duty, after conditioning on vehicle availability, cost, and other constraints.

[17] Guidehouse selects medium and heavy-duty classes based on those use cases with current or projected PEV MHDV model availability and sufficient market data available to support the analysis. Duty is defined by gross vehicle weight (“GVW”) class, where LDV are GVW classes 1 through 2, MDV are GVW classes 3 through 6, and HDV are GVW classes 7 through 8. https://afdc.energy.gov/data/10380

Figure 12. VAST LDV, MDV, and HDV Input Sources – State Example



Source: Guidehouse

A.4 Major Model Inputs

Guidehouse generalized the extensive list of VAST parameters for ease of presentation in this document. **Table 8** lists select data inputs considered within the model along with their respective primary parameter impacts. Most parameters have sub-parameters and are multidimensional.

Table 8. List of Major Model Inputs

Category	Input	Description	Input
LDV, MDV, and HDV Market Characteristics	LDV, MDV, and HDV Population (All Powertrains)	Distribution of vehicle population by age and powertrain.	Infrastructure
	New Vehicle Market	Historic and forecast LDV, MDV, and HDV sales.	Sales
PEV Market Characteristics	PEV Population	PEV registration by powertrain and model year.	Adoption Rate
	Model Availability	Number of powertrain options available within market.	Sales
	Energy Efficiency	Rate of energy consumption.	OPEX
	BEV Range	Maximum distance traveled on full battery state of charge by BEV.	CAPEX, OPEX
	PHEV e-drive utilization	Percentage of travel completed on behalf of battery power.	OPEX
Demographics	Educational Attainment	An indicator of PEV awareness as defined by an understanding of the realities and economics of PEV ownership.	Awareness – ZIP code or Tract

Category	Input	Description	Input
	Income	An indicator of a population's eligibility to finance a new vehicle, PEV purchase.[18]	Eligibility – ZIP code or Tract
	Housing stock	This input applies to LDVs only; an indicator of a population's eligibility[19] to make the best use of the benefits of PEV ownership via a dedicated off-street parking location at a residence.	Eligibility
	Population Density	Reflects the differences in sub-state populations on a spectrum between urban and rural based on 2017 registrations data.	Market Size
Infrastructure	Infrastructure	Existing and forecast infrastructure installations by use case.	OPEX, Eligibility
TCO – Purchase Cost	Battery Cost	Cost of batteries measured on $/kWh basis.[20]	CAPEX
	Other Vehicle Costs	Determines cost structure of PEV and competing powertrain options.[21]	CAPEX
	Regulations	Determines cost of competing powertrain options via OEM subsidies.	CAPEX
	Purchase Incentives	Reduces costs of specific powertrain options through non-OEM subsidies.	CAPEX
TCO – Operating Cost	Fuel Prices	Energy resource costs of competing fuels.[22]	OPEX
	Maintenance	Recurring costs for brake, oil, and tire replacements, varies by powertrain.[23]	OPEX
	Sacrifice	Consumer costs to satisfy alternative transportation mode use.	OPEX
TCO – Resale Value	Ownership Period	Estimated length of first ownership cycle.	TCO

[18] Guidehouse recommends clients consider efforts to interview customers to collect primary data to inform regional willingness to pay for medium and heavy-duty PEVs due to low market data availability for these segments.

[19] Guidehouse assumes that multi-unit dwellings ("MUD") are eligible for EV adoption in proportion to local MUD and public charging infrastructure. Eligibility of MUD grows over time as MUD charging becomes more prevalent, based on action plans such as California's 2016 ZEV Action Plan.

[20] Note that EV battery pack costs have not yet reached price points that would enable *mass market* EVs to have the equivalent range of an internal combustion engine vehicle ("ICEV") (~300 miles); a threshold widely regarded within the industry to prompt a "hockey stick" effect—or significant increase—for PEV adoption.

[21] Other vehicle costs represent "body-in-white" costs by powertrain type, which include non-ICEV costs.

[22] Retail prices are average prices in nominal dollars for a base fixed charge, plus volumetric rates with two tiers. Guidehouse notes that these retail prices may change going forward, thereby impacting the results of client analyses accordingly.

[23] Maintenance costs include diesel emissions fluid for medium and heavy-duty vehicles.

Category	Input	Description	Input
	Depreciation	Resale value as a function of ownership period.[24]	TCO
Awareness	Awareness (Direct)	Overall customer familiarity with PEVs, including but not limited to economics. Influenced through direct outreach.	Awareness
	Word-of-Mouth Effects	Peer-to-peer communication regarding EVs.	Word-of-Mouth Strength
	Marketing Effects	External marketing, through advertising.	Marketing Strength

Source: Guidehouse

A.5 Model Limitations

Although structural models like VAST allow for detailed forecasting of non-linear systems, they do have limitations, especially when applied to emerging or nascent systems. Key assumptions and limitations are as follows:

- **Consumer Choice Modeling:** Guidehouse's determination of the long-run equilibrium market share for PEVs, given complete awareness of the vehicle, is driven primarily by a logit model taking in the TCO (among other non-monetary vehicle attributes such as infrastructure and vehicle availability). The logit model attributes market share to various vehicle types based on economic competitiveness.

  Two limitations to this method in addressing future analyses include:

  - Consumers are less likely to examine the input to the true vehicle TCO as rigorously as the Guidehouse TCO analysis. Customer decision-making can be determined by simplifying heuristics, conventional wisdom, and economically irrational decision rules. The degree to which customers are rational and the diverse decision-making criteria possible in vehicle selection are only modeled in VAST at the powertrain level (BEV vs. PHEV vs. HFCV vs. ICE vehicle).
  - Consumers are likely to have diverse valuations of other non-financial variables (e.g., aesthetic preference, interior selection, perceived safety, perceived environmental benefits)[25] that have not been quantified to Guidehouse's satisfaction at a rigor suitable for inclusion in this methodology. Guidehouse regularly evaluates offerings from our data partner network to identify data points and sources that meet our requirements for verifiable rigor and intellectual consistency with our methodology for incorporation in client analyses. Rather than explicitly quantifying the contribution to customer preference of all these factors,

[24] Model assumes most PEVs are leased or have short-term ownership in the near-term. For LDVs, the residual value ("RV") set by organizations such as the Automotive Lease Guide ("ALG") is typically several percentage points lower than for the equivalent ICEV. This reduced RV can have a negative impact in the TCO of a PEV. For MHDVs, the model assumes a 10-year ownership period.

[25] Guidehouse Insights' national EV consumer survey asks PEV owners to identify financial and non-financial factors that motivated the purchase or lease of a PEV, such as fuel cost savings, owner maintenance costs, financial incentives, ability to charge at home/not use a gas station, technology features, ride comfort, being environmentally friendly, emissions reduction, and energy independence. https://guidehouseinsights.com/news-and-views/consumer-survey-indicates-core-audience-needs-expansion.

Guidehouse allows an intercept term in the logit model to capture the combined effect of non-economic factors.

- **General Vehicle Market Data:** Data on where vehicles are sold is not necessarily indicative of where they will be registered. Moreover, data on where they are registered is not necessarily indicative of where the vehicle will remain for its entire life or where it will refuel.

  To make use of all LDV registration data in the marketplace, Guidehouse typically uses granular registration data from IHS Markit alongside available local registration data and travel data from state transportation agencies. Advantages to this hybrid approach include additional granularity in powertrain and owner attribution from IHS Markit and use of registration coverage from two data sources.

- **MHDV Data:** Market data for MHDV powertrain adoption, vehicle and infrastructure economics, and utilization and efficiency, lacks in rigor and reliability relative to data on LDVs. This gap occurs because the MHDV market is far more diverse than the LDV market in terms of vehicle types and uses, and far smaller than the LDV market in terms of volume. Further, MHDV sales to date for some vehicle classes are limited to proof of concepts and pilots; however, this will change in the next few years. Due to these conditions, many MHDV sales are customized, making data collection and organization difficult and costly.

  Additionally, the market for new MHDVs is highly sensitive to fleet purchasing patterns that can have material impacts on the accuracy of sales and population forecasts at sub-national levels. Consequently, Guidehouse recommends that third-party data be supplemented with client-specific data in the target territory.

- **Transportation Electricity Costs:** Electricity costs at public charging stations vary considerably based on charging station location, charging station type, and pricing model. The market for public charging services is maturing quickly and station owners experiment with fixed rates for charging sessions or rates based on kilowatt capacity or duration of charge. Some charging station owners provide free electricity to attract consumers, while others do so as a benefit to employees. Non-public charging use cases may also realize varied rates based on enrollment in smart-charging programs, which would likely discount electricity costs. Further, demand changes can alter the economics of electrification significantly when DC fast charging is used. Guidehouse recommends more granular analysis—such those performed by VAST Load Impact and Managed Charging modules—to estimate and project transportation electricity costs should clients identify variable rates as a priority for improved precision in future analyses to support forecasting, program design, and implementation, or other transportation electrification activities.

Appendix B. VAST Charging Needs Whitepaper

B.1 Introduction

After modeling the penetration of plug-in electric vehicles[26] ("PEV" or "EV") by duty, class and powertrain, VAST forecasts the amount of electric vehicle supply equipment ("EVSE") required to support those vehicles. A unique attribute of electric mobility is the diversity and interaction of the vehicle and charging ecosystem. A single residential EV may charge at a home "charging station port,"[27] a commercial port at a workplace, or a commercial port at a destination or en route. These ports could be a variety of technology levels, ranging from a 1.1 kW Level 1 to a 350 kW DC fast charge port. Fleet vehicles similarly may be charged at the depot, en route, or at a given destination. Modeling the future of the charging ecosystem is critical to understanding electric mobility impacts, potential business models, and planning for sufficient infrastructure on both the utility and customer side of the electric meter to support the EV owner experience.

One of the most well-documented market barriers for EV adoption is "range anxiety."[28] According to recent surveys, charging station availability remains a top barrier to EV ownership, and has been for as long as this research has taken place.[29] The existing gap between public charging supply and demand[30] means that there is a supply/demand imbalance between the supply of charging from the existing charging network and the demand for charging by EVs. This concept is understood by consumers,[31,32,33] recognized at the federal level, and is in fact foundational to the National Electric Vehicle Infrastructure ("NEVI") program funded by the Infrastructure Investment and Jobs Act ("IIJA"). This gap is potentially widening over time as demand for charging continues to outstrip supply both in absolute terms and rate of growth.

VAST is designed to model the charging network equilibrium over time as a function of vehicle adoption, allowing the charging gap to be explicitly quantified by different charging use cases. Estimating the charging network equilibrium is not just of concern to charging network providers and OEMs. It is becoming central to Utility planning functions across several key areas:

- **Increased demand for electricity**: As the number of EVs on the road grows, there will be an increase in demand for electricity to refuel those vehicles. Developing the utility side EV supply infrastructure to serve the increased electricity demand at premises hosting EV charging will provide a new source of costs and revenue for utilities. Over time, electric rate design that is mindful of, and keeps pace with, charging network buildout can help utilities mitigate cost of service. Outcomes will depend on many factors, including forecasting and planning, that seek to understand and pursue the

[26] Plug-in electric vehicles ("PEV") include battery electric vehicles ("BEV") and plug-in hybrid electric vehicles ("PHEV")

[27] An electric vehicle charging station port is distinct from a charging station (commonly referred to as "charger"), which may have more than one port, and a site, which is the geographic location of the station. The battery charger in the vehicle is described as the "onboard vehicle charger."

[28] Neubauer, Jeremy, and Eric Wood. "The impact of range anxiety and home, workplace, and public charging infrastructure on simulated battery electric vehicle lifetime utility." *Journal of power sources* 257 (2014): 12-20.

[29] **https://www.jdpower.com/business/automotive/electric-vehicle-experience-evx-public-charging-study**

[30] **https://betterenergy.org/wp-content/uploads/2023/01/EV_CorridorRoadmap2023.pdf**

[31] **https://www.jdpower.com/business/automotive/electric-vehicle-experience-evx-public-charging-study**

[32] **https://pluginamerica.org/wp-content/uploads/2022/03/2022-PIA-Survey-Report.pdf**

[33] **https://www.media.volvocars.com/us/en-us/media/documentfile/249123/volvo-reports-the-state-of-electric-vehicles-in-america**

charging network equilibrium. For example, managed charging programs can encourage charging to occur during mostly off-peak periods when electricity supply is high, and demand is low.

- **Grid stability**: Proper integration of managed charging protocols from time of use rates, direct load control, and pricing optimization can help ensure the stability of the grid and prevent overloading the system. Utilities can work with EVSE providers to develop demand management programs and optimal port locations that can limit the impact of EVSE on the grid and better utilize utility assets already on the ground.
- **Improved customer relationships**: By providing convenient and accessible charging options, utilities can improve customer satisfaction and increase customer loyalty.
- **Opportunity for innovation**: The development of EVSE provides an opportunity for utilities to innovate and test new technologies and business models, such as using the charging infrastructure to provide grid services and store excess generation from intermittent or non-dispatchable sources.

This paper demonstrates Guidehouse's best-in-class methodology for modeling EVSE needs and what the future network will look like. After adoption, this is the next step in a holistic modeling approach to EV and EVSE impact forecasting.

B.2 VAST Charging Needs Methodology

The VAST Charging Needs module was designed to forecast the charging needs of vehicles on the road by technology (Level 1, Level 2, direct current fast charge) and use-case (Home, Public Market, Workplace, Fleet Depot, Hub, Curbside, etc.). This EVSE creates a network from which vehicles may charge given the compatibility of an EVSE use-case and the vehicle type. The data sources used in VAST are continuously evolving with the EV and EVSE landscape. VAST uses the best available data from a combination of public, Guidehouse proprietary, and anonymized utility partner sources. Guidehouse evaluates new data sources as they are made available for validity, reliability, affordability, and compatibility to make sure that our assumptions keep pace with the rapidly evolving market. As such, the sources and assumptions in this paper will be updated continually.

B.2.1 Methodology Overview

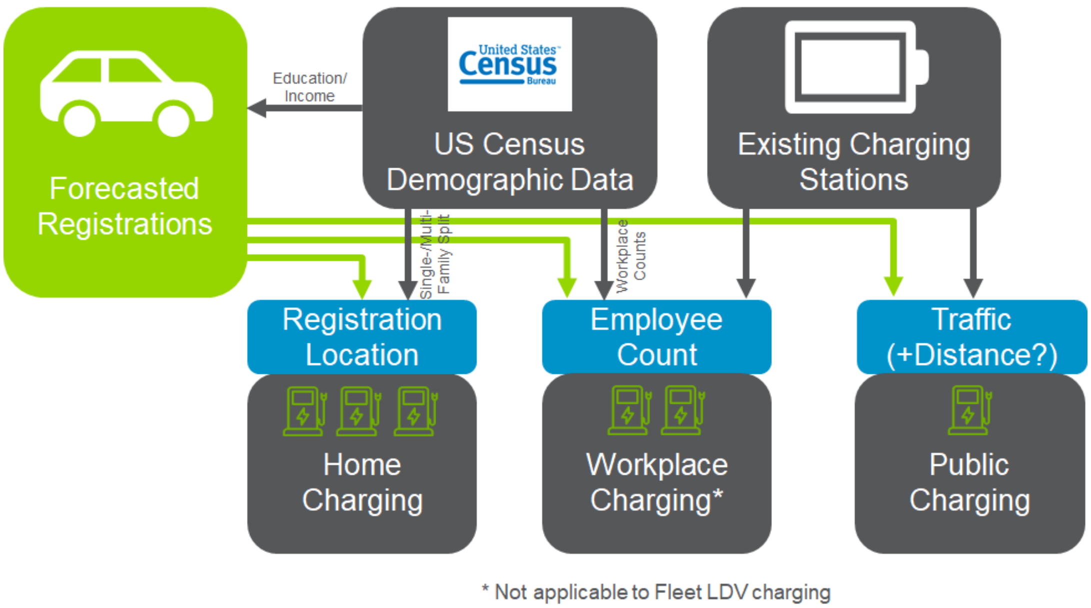
Charging build-out has feedback with the adoption forecast. The range anxiety market barrier is driven by the lack of public charging, which in turn is driven by the lag between vehicle adoption and charging infrastructure development. As a consumer, to be comfortable replacing all driving with electric driving means access to a combination of at-home, en route, and destination charging options. To be comfortable with purchasing a battery electric vehicle ("BEV"), a consumer must be confident that a large portion of their driving needs can be met. For most drivers, this means longer trips and a large pool of ports en route and at destinations. Charging providers on the other hand need to have some confidence in covering their costs to invest in EV charging infrastructure, which requires a large base of drivers. This seeming paradox is likely behind the slow roll-out of public charging infrastructure and the persistence of charging access as a barrier to adoption.

In VAST, the EVSE market is assumed to fundamentally follow the vehicles on the road. This means that while there might be individual areas where occasionally the EVSE is "overbuilt" given the electric vehicle traffic, the dominant trend will be EVSE lagging vehicles on the road, and thus the EVSE market will tend to be under equilibrium as long as vehicle sales increase.

B.2.2 Calculating Infrastructure Requirements

Fueling infrastructure and vehicle populations evolve together in VAST. More vehicles on the road with specific fuel requirements dictated by the powertrain stimulate infrastructure development for the relevant fuel. This is accomplished through the estimation of dynamic regional vehicle-per-charger ratios. They are regional, reflecting local traffic and driving patterns, and dynamic, reflecting changing technology, range, and use case preferences among drivers. Charging levels (rated capacity) evolve over time in the model in response to vehicle range, penetration, and use case requirements. **Figure 13** shows how the light duty vehicle forecast interacts with the charging needs by use-case.

Figure 13. Guidehouse Methodology for Connecting Charging Stations with Individually Owned LD Vehicle Registrations



Source: Guidehouse

Home Charging in VAST

Home charging plays a critical role in the EVSE network today, as the majority of early adopter EV owners have access to dedicated home charging at either Level 1 or Level 2[34]. We currently are likely at or near maximum home charging as a share of total daily charging sessions relative to other use-cases.[35,36] It is also worth noting that for a trip to rely solely on home charging, the trip must be limited to at most 50% of the effective vehicle range[37], and factors such as highway driving, weather, tire pressure, heating, ventilation, and air conditioning ("HVAC") use and departing state of charge all have large impacts on range, meaning that maximum trip distance

[34] **https://www.nrel.gov/docs/fy22osti/81065.pdf**

[35] Powell, Siobhan, et al. "Charging infrastructure access and operation to reduce the grid impacts of deep electric vehicle adoption." *Nature Energy* 7.10 (2022): 932-945.

[36] Lee, Rachel, and Solomon Brown. "Social & locational impacts on electric vehicle ownership and charging profiles." *Energy Reports* 7 (2021): 42-48.

[37] Assuming flat terrain without towing, battery swapping, or other unconventional range extension.

relying solely on home charging would be greatly reduced. In the long run, the number of EV owners with access to home charging will vary regionally, likely following the percentage of vehicle owners with single unit dwelling residences.

Workplace Charging in VAST

Workplace charging is second only to home charging in terms of residential driver preference.[38] Drivers without access to home charging will often rely on workplace charging as their primary plug-in location. As such, workplace charging is seen as a critical use-case to expanding electric transportation beyond early adopter populations.[39] In VAST, workplace charging is modeled as a function of home charging access, total charging need, and market maturity. Because workplace charging does not coincide with the vehicle's registered location, modeling the location of these ports means identifying workplace locations, sizes, and proximity to public stations.

Public Charging in VAST

Guidehouse sources existing charging sites from the Department of Energy's Alternative Fuels Data Center ("AFDC") and calculates the charging network support level given the number of registered PEVs on the road. However, there is strong evidence that suggests that public network is not adequate to support the current level of vehicles on the road. As EVs expand to more use cases and support additional driving patterns, the need for public charging will increase.

EV charging infrastructure needs vary from state to state, reflecting their unique populations, economies, and topographies. Fortunately, differences in EV adoption, driving patterns, density, road network structure, weather conditions, and vehicle mix are directly accounted for in VAST in the estimation of long-run charging needs. To estimate the future equilibrium state between vehicles and EVSE, Guidehouse utilizes the National Renewable Energy Laboratory's ("NREL") EVI-Pro model.

The EVI-Pro model is data-driven model that projects the demand for EV charging infrastructure in the United States based on various scenarios and assumptions about the future growth of the EV market. The model accounts for factors such as the number of EV supported, range, powertrain mix, amount of home charging available, existing public networks, consumer driving patterns, and preferred charging behavior to estimate the demand for EVSE for a specified geography.

The sensitivities of the EVI-Pro model to input assumptions at a national level are shown in **Figure 14**.[40] Model sensitivity is an important analysis that can inform a researcher's parameter value selection but should not be taken out of context. The two most important contextual factors grounding sensitivity analysis are the unit basis of the inputs, and the likelihood (uncertainty) around a change in input. The unit basis refers to the denomination of the sensitivity – for example "PEV Count" is in units of vehicles (continuous), while "PHEV Support" is a categorical unit with only three options. If PHEV Support were to be categorized as a

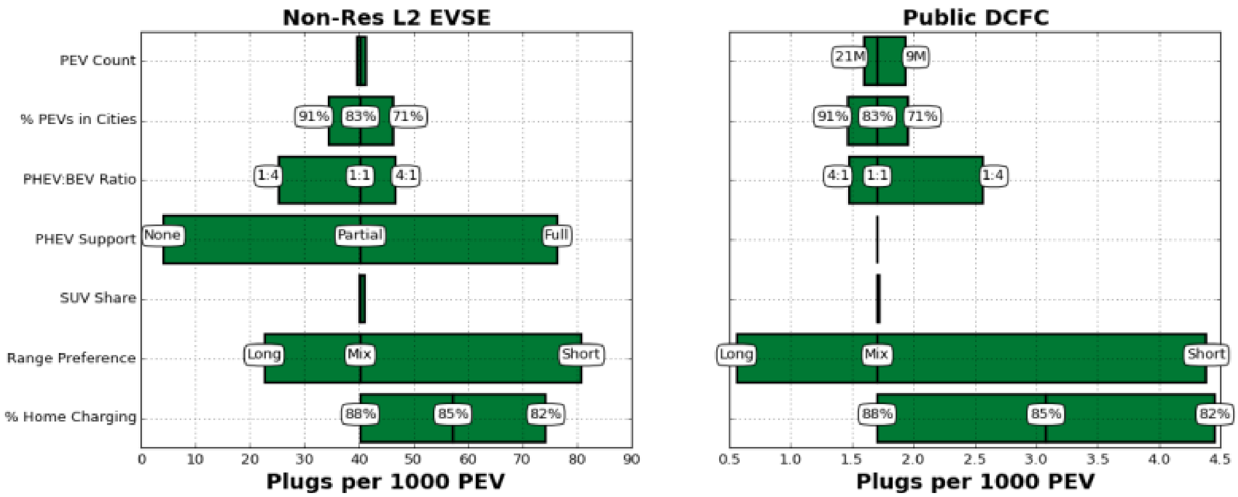
[38] Dixon, James, et al. "On the ease of being green: An investigation of the inconvenience of electric vehicle charging." *Applied Energy* 258 (2020): 114090.

[39] Hsu, Chih-Wei, et al. "City charging infrastructure needs to reach 100% electric vehicles: The case of San Francisco." *The International Council on Clean Transportation* 18 (2020).

[40] **https://www.nrel.gov/docs/fy17osti/69031.pdf**

continuous variable, it would by definition appear less sensitive. The likelihood refers to the probability, given empirical trends, of a unit-wise change in the input. A one-unit variation in some inputs are highly uncertain, such as PEV Count, while a one-unit variation in others are less uncertain, such as "% Home Charging". Thus, while the model appears highly sensitive to several key inputs, this is likely overstated for a few reasons discussed below having to do with likelihood of unit-wise change.

Figure 14. Sensitivity of NREL's EVI-Pro Model to Input Assumptions



Source: NREL National Plug-In Electric Vehicle Infrastructure Analysis.

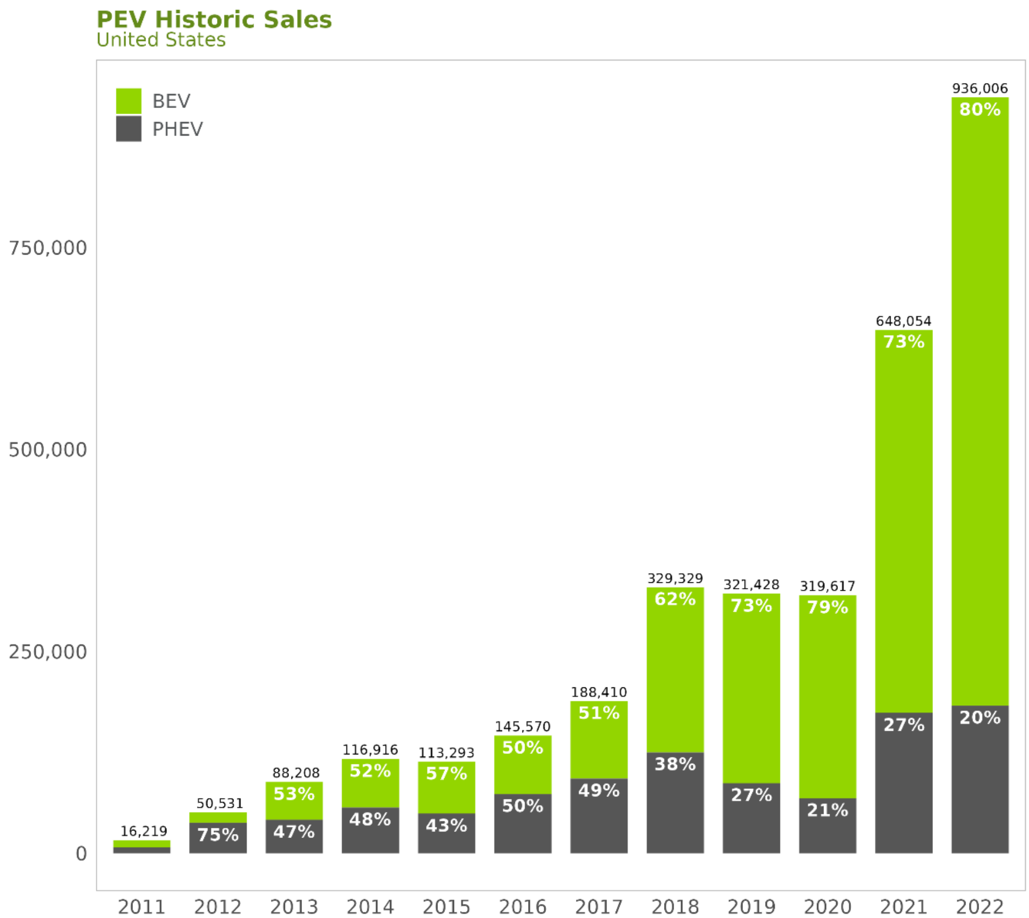
- **PHEV/BEV Ratio**. Guidehouse scenario modeling suggests that PHEV adoption will likely fall in a low, and narrow range. A future with high penetration of PHEVs would require the reversal of three major trends:
    - Current automaker investment, which is the strongest leading indicator of future model availability and production, points strongly in favor of diminishing PHEV penetration. Between 2025 and 2035, 11 of the 15 largest automakers have committed to at least 50% BEV sales. The four Japanese automakers that still plan on supporting hybrid powertrains have already started to back away from their commitments to PHEV or fuel cell electric vehicle ("FCEV") technology. [41] Automaker sales targets are matched with investment spending, as worldwide, publicly released commitments add up to around $1.2 trillion to BEVs. [42]
    - Customer preference, as measured by vehicle sales trends, also indicates the predominance of BEVs going forward. About 92,000 PHEVs were sold in United States in 2017. In the same year, about as many (96,000) BEVs were sold in the United States. In 2022, the number of BEVs sold had increased to nearly 752,000 per year, while PHEVs had only increased to 183,000. This shift to customer preference for BEV (from approximately 51% in 2017 to approximately

[41] For example: **https://newsroom.toyota.eu/toyota-motor-europe-outlines-its-path-to-100-co2-reduction--by-2035/**

[42] **https://www.reuters.com/technology/exclusive-automakers-double-spending-evs-batteries-12-trillion-by-2030-2022-10-21/**

81% in 2022) is illustrated in **Figure 15** below, showing national vehicle sales by powertrain from 2011-2022. As public charging infrastructure expands, the current demonstrable customer preference for BEVs is expected to accelerate.

Figure 15. Annual Sales of BEVs and PHEVs in United States, 2011-2022



Source: Guidehouse, IHS Markit

- Policy treatment is moving away from support for PHEVs. The California Air and Resource Board's ("CARB") Zero Emissions Vehicle program, specifies that automakers will not be able to meet more than 20% of their Zero Emissions Vehicle ("ZEV") requirement through PHEV sales. Including other states that have adopted California's ZEV targets accounts for about 40% of vehicle sales in the United States. While policies such as the Inflation Reduction Act currently treat both PHEVs and BEVs as ZEVs and both get somewhat equal access to incentives, evidence of a relatively low real-world electric share of PHEV miles[43] can be expected to challenge legislative support for PHEV incentives in the future. Further, policies supporting PHEVs in Europe are sunsetting, and nations are considering ending those policies as early as next year. This is largely driven by PHEV emissions impacts being larger than previously assumed. These global

[43] Isenstadt, Aaron, Zifei Yang, Stephanie Searle, and John German. "Real World Usage of Plug-in Hybrid Vehicles in the United States." (2022).

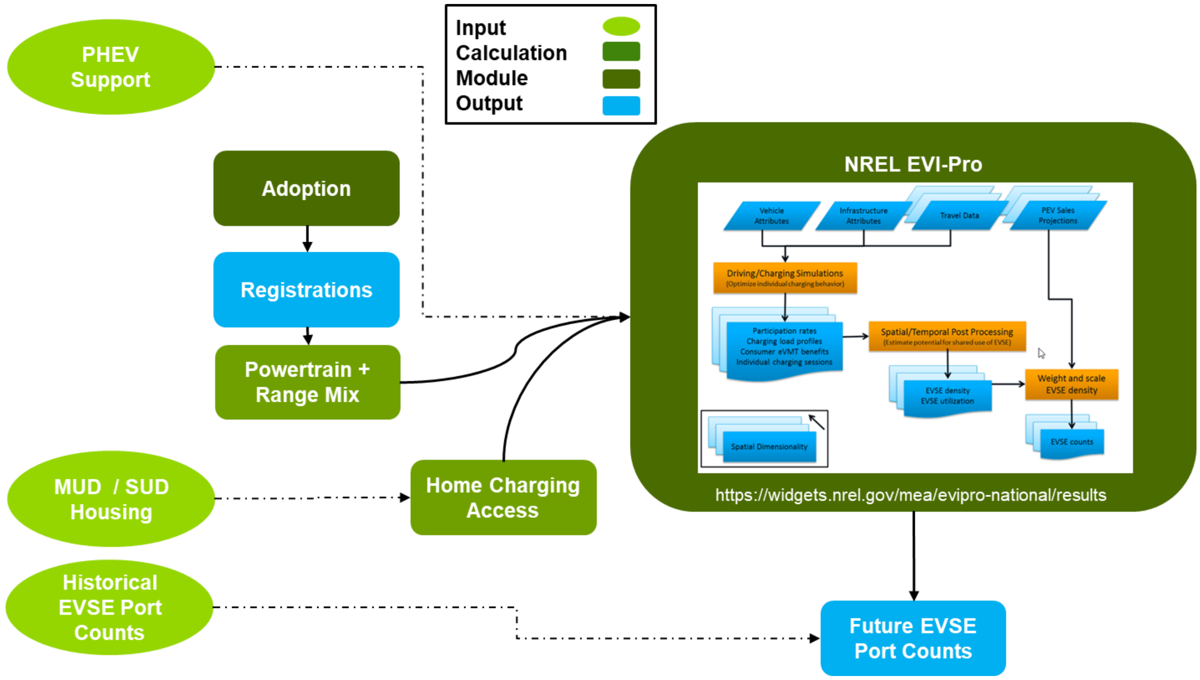
policy trends away from PHEV support are expected to reduce supply and demand for these vehicles worldwide.

- **Range Preference**. Range preference is already shifting significantly toward longer range vehicles, possibly because of the lack of reliable public charging. Over 75% of 2022 BEV sales were at or above NREL's long range bin (250 miles), using the EPA's combined city/highway range estimates. This is a conservative assumption, as lower range vehicles would require a more robust public charging network. As of model year 2022, the median EPA combined range for new BEVs was 256.[44]
- **PHEV Support**. Guidehouse recommends building Level 2 networks to fully support electric driving of PHEVs when used in concert with home charging. The majority of this Level 2 network should include market ports at destinations like shopping centers and public parking areas. These locations provide opportunities for PHEV drivers to top off their batteries during the day while they are parked for extended periods. This helps to extend the electric driving range of PHEVs. Like all others, this variable can be explored in scenario analysis.
- **Home Charging**. Nationally, home charging currently supplies about 80% of total vehicle energy[45]. This percentage is expected to decrease with market expansion as workplace, destination, and en route charging become larger shares of a given vehicle's daily charging sessions. Home charging also will decrease as consumers without access to dedicated home charging increasingly purchase EVs.

Figure 16 illustrates the data flows in VAST starting with the output of the Adoption module and ending with the output of future EVSE Port Counts. The module employs a dynamic market equilibrium model to estimate the size of the existing public charging gap (if any), and the transition to market equilibrium in a future state.

[44] **https://www.fueleconomy.gov/feg/evsbs.shtml**
[45]**https://avt.inl.gov/sites/default/files/pdf/arra/PluggedInSummaryReport.pdf**

Figure 16. VAST Public Charging Needs



Source: Guidehouse

The transition between current state x_1 and equilibrium state x_2 is modeled through a transition function for each period *t*. For example, if this transition is linear, it would be represented in **Equation 4**:

Equation 4

$$\boldsymbol{x_t = x_1 + (x_2 - x_1)(\frac{t}{T})}$$

The benefit of a linear transition is that there is only one tuning parameter (*T*) representing the time period at which the market reaches equilibrium. A more reasonable assumption is a sigmoid transition function for each period *t*, with *k* and *c* determining the shape of the curve, for example:

Equation 5

$$f(t) = \frac{1}{1 + e^{-kt+c}}$$

VAST can model a variety of transition functions between the current state and equilibrium state. The most appropriate will depend on the level of market activity, build rate, and funding mechanisms in the state. In each case, the function parameters should be fitted to historical data where appropriate.

While the volume of ports is calculated by transitioning between historical network characteristics and the long-run network characteristics as described above via a dynamic market equilibrium model (the number of ports required to supply a given number of vehicles) the locations of these charging ports can be difficult to determine through the vehicle counts alone. The Siting module[46] is used to calculate the latitude and longitude of likely public charging sites to inform distribution planning, EVSE siting, and other locationally sensitive analyses.

The Role of Weather, Climate, and Topography

Effective driving range is a key consideration for electric vehicle owners, since vehicles with longer effective ranges can more fully replace ICE driving needs. In NREL's EVI-Pro model, default vehicle efficiency is assumed to be between 4.3 and 4.4 miles per kWh, which best reflects passenger cars in city driving conditions. Even under EPA testing conditions, which are biased toward city driving, the average vehicle efficiency of the fleet nationally was 3.54 as of 2020. In real-world conditions, efficiency can be materially lower. For example, BEV light trucks in winter months at highway speeds can travel about 2 miles per kWh. Lower efficiency would result in greater EVSE needs. Just as charging needs are a function of vehicle range, vehicle range is a function of vehicle efficiency, which is affected by local climatic factors.

Consequently, the following factors may require higher port density and network coverage on a regional basis[47]:

- **Temperature while Driving**. Vehicle range is determined by temperature due to two factors. The first is cabin temperature. The HVAC system in the vehicle consumes energy from the vehicle's main battery. Even in moderate temperatures in city-driving conditions, this can decrease effective range by about 30%.[48] The greater the difference between the desired cabin temperature and the outside temperature, the more energy consumed by the HVAC system. Most PEVs also have temperature regulation controls in their battery management system, meaning that the vehicle must draw energy to keep the battery within a temperature range conducive to the electro-chemical reactions in the battery cell, further reducing range.
- **Temperature while Charging**. Charging time can also be influenced by temperature. Researchers at Idaho National Lab found that charging times at direct current fast charging ("DCFC") stations could be as much as three times higher in colder climates to reach the same state of charge.[49] **Figure 17** shows the predicted end state of charge ("SoC") of a Nissan Leaf charging for 30 minutes at an outdoor 50kW DCFC, from an initial SoC of 20%. Northern states demonstrate greatly decreased effective charging rates. Therefore, it is important to factor the impact of higher charging times in colder climates into planning for charging infrastructure needs.

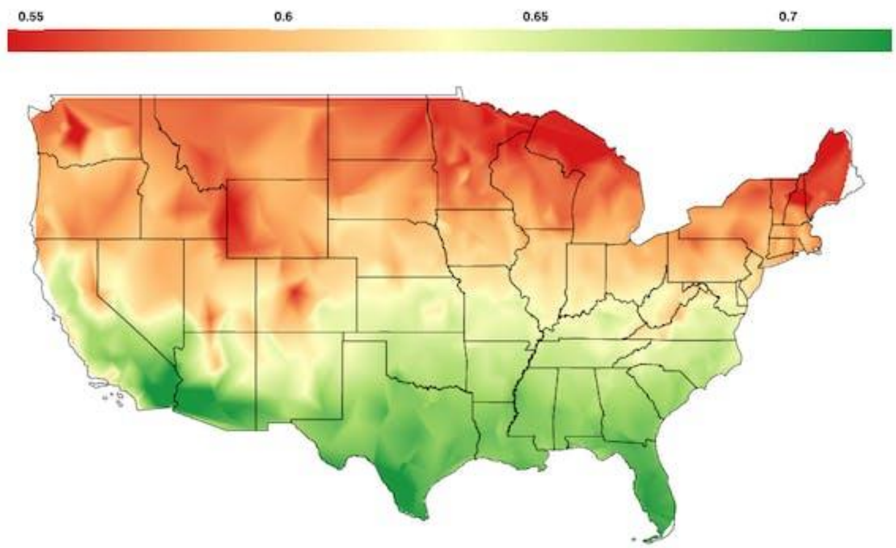
[46] The VAST Siting module uses a GIS network model built in Python using the ArcPy library to optimally site EV ports based on local vehicle populations and vehicle miles traveled for a specified street network.

[47] For example, by increasing PHEV share to reflect greater secondary market uptake or decreasing effective vehicle range.

[48] Al-Wreikat, Yazan, Clara Serrano, and José Ricardo Sodré. "Effects of ambient temperature and trip characteristics on the energy consumption of an electric vehicle." *Energy* 238 (2022): 122028.

[49] Motoaki, Yutaka, Wenqi Yi, and Shawn Salisbury. "Empirical analysis of electric vehicle fast charging under cold temperatures." *Energy Policy* 122 (2018): 162-168.

Figure 17. Predicted Battery State of Charge on a Median Temperature Day



Source: Idaho National Laboratory, 2018[50]

- **Humidity, Wind and Elevation**. High humidity increases air resistance, which is a significant factor in EV highway driving range. Extra moisture increases the density of the air, requiring more energy to move through it. Because air resistance (*R)* is a function of air density (*D*) multiplied by the frontal area of the vehicle (A_f*, where f is the rolling resistance of the vehicle)* and the drag coefficient (*C)* and velocity (*v)* squared, this has non-linear impacts on trucks and SUVs with at highway speeds:

Equation 6

$$R = \frac{1}{2}\ D\ A_f\ C\ \left(\frac{v}{3.6}\right)^2$$

Strong headwinds can also affect EV driving range through increased air resistance. Topographically speaking, elevation impacts gradient resistance, which can reduce range when going uphill, and increase range when going downhill, especially when paired with regenerative braking. Gradient resistance (G), can be calculated as a function of the weight of the vehicle (*w*) and the angle of the gradient (*x*):

Equation 7

$$\boldsymbol{G = \pm w\ \sin\,(x)}$$

Consequently, regions where high humidity, strong winds and varying elevations are common, it may be necessary to increase port density and charging network coverage.

[50] Motoaki, Yutaka, Wenqi Yi, and Shawn Salisbury. "Empirical analysis of electric vehicle fast charging under cold temperatures." *Energy Policy* 122 (2018): 162-168.

Fleet Charging

Commercially owned vehicles have significantly different duty cycles, charging behavior, and charging requirements than personal vehicles. While many of the same calculations apply to fleet charging needs assessment, special modeling is recommended as it will enhance the forecast accuracy.

- **Fleet Targeting.** In jurisdictions where fleet activity is of high relevance, fleet locations can be determined though a dedicated targeting analysis. This consists of collecting individual fleet data for the largest fleets in operation for a given jurisdiction, including number of vehicles by make and model, fleet type, operating duty schedule, miles traveled, age, fuel, operator characteristics, and other key metrics. These data are used to develop regional electrification forecasts that can supplement VAST commercial fleet adoption results that rely primarily on registration data.
- **Depot Charging.** Depot charging is a method of charging for fleet EVs that involves installing charging infrastructure at the vehicle's hub for back to base charging. Diverse vehicle classes including light, medium, and heavy-duty trucks, school buses, transit buses, delivery trucks, and freight vehicles are eligible for depot charging. The charging infrastructure would be used to charge the vehicle before and after the duty cycle, as well as during idle time, such as when the vehicle is parked overnight or between trips in a “hub-and-spoke”[51] model. Depot charging is a preferred charging method for fleet vehicles as it allows for more control over the charging process and is expected to constitute the large majority of charging needs of light, medium and heavy-duty fleets.[52] Based on the number of vehicles in a fleet, battery capacity and the charging technology employed the charging to vehicle ratio can for depot charging may vary between 0.5 to 1 (high ratio suggests limited to no sharing of charges between vehicles).[53] In addition, the potential for fleet operators to manage charging costs is a critical element of depot charging. For more information, refer to Guidehouse’s VAST Managed Charging paper.
- **Hub Charging.** For medium and heavy-duty vehicles not using a hub-and-spoke delivery model, en route charging is critical to the success of electrification. Freight, trucking, and other fleet operators fitting this model currently rely heavily on en route refueling for gasoline and diesel vehicles. Large heavy trucks (class 7 and 8) that drive long distances to deliver goods from ports or production facilities to large distribution centers or warehouses will be the best candidate for hub-charging. These trucks mostly cover exact routes with highly predictable distances, with a range of 200 miles or more. The hub charging stations are expected to have very low utilization as it caters to a very specific use case and consequently, hub charging can be more expensive than depot charging because charging-station operators might charge extra fee on their electricity or service to recoup their infrastructure costs. Building of hub charging stations are also expected to benefit from infrastructure incentives laid in the Bipartisan Infrastructure

[51] See O'Kelly, Morton E. "A geographer's analysis of hub-and-spoke networks." *Journal of transport Geography* 6, no. 3 (1998): 171-186.; and Zäpfel, Günther, and Michael Wasner. "Planning and optimization of hub-and-spoke transportation networks of cooperative third-party logistics providers." *International journal of production economics* 78, no. 2 (2002): 207-220.

[52] Fleet electrification resources are predicated on depot charging. See **https://www.epa.gov/smartway/smartway-heavy-duty-truck-electrification-resources**

[53] https://www.fleet.ford.com/content/dam/aem_fleet/en_us/fleet/brochures/order/general-information/2021_FordCV_ChargingGuide.pdf

Law.[54] The development of electric charging stations along major trucking routes will also need to build at higher capacity and be able to accommodate a range of vehicle size and weights. Current commercially available charging standards (50-400 kW) would mean short-term changes in logistics and scheduling. In the long term, initiatives like the Megawatt Charging Standard[55] would solve these logistics challenges but will open additional challenges in distribution capacity.

B.3 Conclusion

The EV charging market is lagging behind the rapidly growing number of electric vehicles on the road. This has the potential to increase as automakers increasingly commit to BEV production, and customer preferences continue the ongoing shift towards BEVs.

VAST quantifies the size of the charging infrastructure gap for a given jurisdiction and provides a forecast of the equilibrium number of charging ports required to support a given electric vehicle forecast. PEV drivers will access a combination of EVSE uses cases to meet their transportation needs. While at home or depot charging will remain a critical piece of the EVSE network, workplace, destination, en route charging are expected to become more significant as EVs proliferate across the globe.

To understand the impacts that the EVSE network will have on the electric grid, the interaction between the vehicles and ports must be simulated to create load shapes for each EVSE use case serving a diverse set of vehicles. This is covered in the VAST Load Impact module.

[54] https://www.whitehouse.gov/briefing-room/statements-releases/2023/02/15/fact-sheet-biden-harris-administration-announces-new-standards-and-major-progress-for-a-made-in-america-national-network-of-electric-vehicle-chargers/

[55] **https://www.nrel.gov/news/program/2020/nrel-hosted-event-supports-industry-development-megawatt-charging-system-connectors.html**

Appendix C. Federal Policies Incorporated into PSCo Forecast

C.1 Introduction

Guidehouse regularly incorporates and updates provisions from federal, state and local policies into the VAST modules to simulate market effects of policy impacts over time. The Inflation Reduction Act ("IRA") of 2022 and the Infrastructure Investment and Jobs Act ("IIJA") of 2021 allocated billions of dollars over the next decade to the expansion of transportation electrification in the United States. In order to model the impacts of policies on electric vehicle adoption, VAST considers both the economic and non-economics dynamics of EV adoption that are affected by new policies. This section details the methods by which Guidehouse incorporated the economic provisions from IIJA and IRA into VAST forecasting for PSCo. We also include relevant state and local incentives that were directly modeled in the VAST Adoption module for reference.

C.2 Inflation Reduction Act of 2022

Considerations from the IRA modeled in the VAST Adoption module appear in **Table 9**.

Table 9. Provisions from Inflation Reduction Act included in PSCo Forecasting

Provision	Description	VAST Incorporation Method
Tax Credit Availability	• Incentives available until 2032	• Applied all IRA provisions in the model through 2023

New Vehicle Eligibility	• Removal of 200,000 vehicles per OEM cap on tax credit
	• Vehicle price maximum:
	  ○ Passenger cars: $55,000
	  ○ Light trucks: $80,000
	• North America materials and assembly requirements:
	  ○ Battery materials requirement only: $3,750
	  ○ Battery components assembly only: $3,750
		• Accounted for incentive eligibility based on the supply chain of models being released through 2024 and the manufacturer suggested retail price ("MSRP")

Income-based Eligibility	• Limit credit to <$300,000 household income	• Accounted for income thresholds and expected price sensitivity
Vehicle Tax Credit	• Light-duty BEVs: $7,500 • Light-duty PHEVs: $5,500 • Medium/Heavy-duty BEV as minimum value of either: 30% of new vehicle cost; incremental cost compared to an ICE equivalent; or $40,000	• Total cost of ownership is reduced according to applicability factors by vehicle segment using historic registration data, model availability, MSRP, and federal guidance on eligible vehicles and demographic data
Used Vehicle Tax Credit	• $4,000 tax credit	• N/A. Vehicle assumed to remain in-state for entire useful life

Provision	Description	VAST Incorporation Method
New Infrastructure Tax Credit	• Up to $100,000 per qualified alternative fuel vehicle refueling property • Level 2 and direct current fast charge	• Increased adoption of charging technologies reduces eligibility constraint, resulting in an increase in light-duty EV adoption

Source: Guidehouse

C.3 Infrastructure Investment and Jobs Act of 2021

IIJA includes nearly $5 billion for the National Electric Vehicle Infrastructure (“NEVI”) Formula Program, which allocates funding to individual States to build out charging stations along designated Alternative Fuel Corridors. At the time of the study, the Colorado NEVI Plan[56] was not released, and as such potential NEVI station locations were not included in the VAST analysis.

IIJA establishes two programs collectively providing over $10 billion for electrifying both transit and school buses (~$5 billion for each bus type). Due to time constraints, these incentives were not incorporated in the study. As such, adoption results for transit and school buses in Colorado are slightly conservative over the years where the programs are in effect, specifically 2022 to 2026.

[56] https://www.codot.gov/programs/innovativemobility/electrification/nevi-plan

Appendix D. VAST Detailed Results Definitions

Acronym/Term	Definition
Vehicle Adoption Analysis	Forecast of adoption of various powertrain, fuel, and vehicle class configurations in census tracts. Values associated with this analysis reflect the population of vehicles for a given year
Charging Needs Analysis	Forecast of charging infrastructure required to support the electric vehicle adoption analysis, calculated though a dynamic market equilibrium model (the number of charging station ports required to supply a given number of vehicles). Values associated with this analysis reflect annual charging capacity or number of ports for a given year
Market Analysis	A bottom-up market forecast of electric vehicle adoption based on market conditions at the time of analysis (September 2022)
Target 2030 Analysis	A goal seeking approach built to result in electric vehicle adoption that meets Colorado's state target of 940,000 LDEVs and to evaluate the charging needs associated with Colorado's adoption goal
Colorado (State-Level)	The state of Colorado. All results under the label "Colorado (State-Level)" relate to results for the entire state.
Colorado (Territory-Level)	The PSCo service territory. All results under the label "Colorado (Territory-Level)" relate to results for PSCo service territory.
PHEV	Plug-in hybrid electric vehicles ("PHEVs")
BEV	Battery electric vehicles ("BEVs")
PEV	Plug-in electric vehicle. Includes both plug-in hybrid electric vehicles ("PHEVs") and battery electric vehicles ("BEVs")
Individually-Owned BEV LDVs	Battery electric light-duty vehicles that are registered to as personal vehicles
Individually-Owned PHEV LDVs	Plug-in hybrid electric light-duty vehicles that are registered to as personal vehicles
Fleet-Owned BEV LDVs	Battery electric light-duty vehicles that are registered to as commercial vehicles
Fleet-Owned PHEV LDVs	Plug-in hybrid electric light-duty vehicles that are registered to as commercial vehicles
Electric MDVs	Both battery electric and plug-in hybrid medium-duty vehicles that are registered as either personal vehicles or commercial vehicles

Acronym/Term	Definition
Electric HDVs	Both battery electric and plug-in hybrid heavy-duty vehicles that are registered as either personal vehicles or commercial vehicles
All Individually-Owned LDVs	All light-duty vehicles that are registered as personal vehicles
All Fleet-Owned LDVs	All light-duty vehicles that are registered as commercial vehicles
All MDVs	All medium-duty vehicles
All HDVs	All heavy-duty vehicles
Port	The device that attaches a vehicle to the charging station (commonly referred to as “charger”) and dispenses electricity into the vehicle. As an analogy, a port would be equivalent to the nozzle attached to a gasoline pump inserted into a vehicle to dispense gasoline.
MW	Megawatt
Private Infrastructure	Electric vehicle supply infrastructure (“EVSE”) where access is limited to specific individuals, such as the home owner or employee
Public Infrastructure	Electric vehicle supply infrastructure (“EVSE”) associated where access is available to the public
Hub L3	Level 3 (i.e., direct current fast charge, “DCFC”) electric vehicle infrastructure associated with public charging of medium and heavy-duty vehicles, such as at an electric truck-stop
Market L2	Level 2 electric vehicle infrastructure associated with public charging in areas near retail stores (grocery, mall, national parks) or on roads to accommodate long-distance driving, such as traditional gas-stations located on highways
Market L3	Level 3 electric vehicle infrastructure associated with public charging in areas near retail stores (grocery, mall, national parks) or on roads to accommodate long-distance driving, such as traditional gas-stations located on highways
Shared Single-Unit Dwelling (“SUD-Shared”) L1	Level 1 electric vehicle infrastructure associated with public home charging at on-street charging stations installed by an HOA to accommodate a neighborhood
Shared Single-Unit Dwelling (“SUD-Shared”) L2	Level 2 electric vehicle infrastructure associated with public home charging at on-street charging stations installed by an HOA to accommodate a neighborhood
Shared Single-Unit Dwelling (“SUD-Shared”) L3	Level 3 electric vehicle infrastructure associated with public home charging at on-street charging stations installed by an HOA to accommodate a neighborhood