Port of New York and New Jersey Drayage Electrification Analysis

Andrew Kotz, Kenneth Kelly, Jason Lustbader, Scott Cary, and Brett Oakleaf

National Renewable Energy Laboratory

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List of Acronyms

BET	battery-electric truck
CAN	Controller Area Network
CO_2	carbon dioxide
FASTSim	Future Automotive Systems Technology Simulator
MPG	miles per gallon
$MTCO_2$	metric tons of carbon dioxide
NO_x	oxides of nitrogen
NREL	National Renewable Energy Laboratory
PANYNJ	Port Authority of New York and New Jersey
PoNYNJ	Port of New York and New Jersey
SOC	state of charge
SO_x	sulfur oxides

Executive Summary

The National Renewable Energy Laboratory (NREL) evaluated the potential for drayage electrification in the Port of New York and New Jersey (PoNYNJ), with a focus on three different drayage operators. This report summarizes the data collection and electrification evaluation of all three drayage operators, includes detailed operational data, and identifies the performance requirements for battery-electric trucks (BETs) and corresponding infrastructure operated within the context of PoNYNJ drayage operation. This report also details a methodology to evaluate opportunities, strategies, and challenges associated with future expansions of BETs in meeting the Port Authority of New York and New Jersey's (PANYNJ) emissions goals.

The PANYNJ has established a goal of achieving net-zero carbon emissions by 2050 across all facilities, including from tenant and stakeholder sources such as drayage trucks [1].

Methodology

NREL used real-world performance data collected on the three PoNYNJ drayage operations, along with modeling and analysis tools to compare BET to diesel trucks. From March to July 2021, NREL collected 1-Hz vehicle and engine data from 46 drayage trucks at the three operators, totaling nearly 121,000 miles of operation, providing enough information to assess truck operations for electrification potential. A Future Automotive Systems Technology Simulator (FASTSim) electric truck powertrain model was validated using PoNYNJ data, and scenarios were run to evaluate drayage truck electrification requirements over the real-world cycles. The first scenario examined BET viability with minimal changes to existing operations. This assumes the trucks charge when stopped for 2 hours or longer, have a functional battery size of 375 kWh, and can charge at 270-kW average, which are the specifications of the commercially available Freightliner eCascadia[1]. The second scenario looked at what operational, charging infrastructure, and BET technology changes would be needed to fully electrify the participating operator's drayage truck fleet. Finally, detailed analysis was run on charging rate structure to understand operational costs to the fleets.

Results

The studied drayage trucks averaged 5.1 miles per gallon (MPG), spent roughly 9% of their energy at idle, and drove an average of 140 miles per day with a maximum daily distance of 573 miles. The FASTSim model results indicate a comparable BET would use 417 kWh of energy per day, on average, accounting for cargo weight, which is close to the full usable capacity of the eCascadia currently available on the market. **With minimal change to operations as outlined below, partial fleet electrification is possible with current technology.** However, some specific days of operation would require over 1,600 kWh of energy due to longer distances traveled by the trucks and more intense operation. Trucks used for long distance and intense operation cannot be readily electrified with current technology without operational changes.

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[1] Other truck models exist with battery sizes ranging from the 375 kWh Volvo VNRe to the 753 kWh Nikola TRE, however, the eCascadia was chosen at the time of modeling because one of the studied fleets had this truck on order. Despite choosing a single battery size for current technology, data on larger battery sizes is provided throughout this analysis to account for improvements in battery technologies and energy densities over time.

Current Operations Scenario (charging only when stopped for 2 hours or more)

Outputs of the first model scenario indicate that with minimal change to operations 4 out of 12 trucks for Fleet 1, 4 out of 9 trucks for Fleet 2, and 1 out of 22 trucks for Fleet 3 could complete all the measured daily routes using currently available BET technology and charging only during dwell periods (engine off) of 2 hours or longer at a rate of 270 kW.

This would indicate that the existing Fleet 2 routes are the best near-term candidate for drayage electrification, followed by Fleet 1. The shorter routes of these fleets reduce overall energy requirements and provide more time for truck charging. Based on the data collected, it appears unlikely that all fleet operations could be fully electrified using current BETs without operational or technology changes. However, the shorter routes from each fleet could be electrified, but this may require operation changes to constrain the truck to only those shorter routes.

Full Electrification Scenarios

The second category of modeled scenarios explored requirements for full electrification, which can both serve as an outline for PANYNJ in planning for future requirements and inform manufacturers when designing their next generation of BETs to meet real-world drayage requirements and send a signal to electricity providers regarding infrastructure needs and expected utilization. Assuming partial to full charging for each charging opportunity specified, the individual scenarios for fully electrifying each fleet are:

> *Scenario 1:* Results indicate that as larger battery options become available, Fleet 1 trucks could be fully electrified (all measured routes) with a 1,500-kWh battery and 175-kW charge rate; Fleet 2 trucks could be fully electrified with a 1,375-kWh battery and 100-kW charge rate; and Fleet 3 trucks could be fully electrified with a 1,600-kWh battery and 175-kW charge rate—all when charging for dwell periods of 2 hours or more.
>
> *Scenario 2:* Increasing battery size, but also charging more frequently throughout the day to include 50-minute dwell periods, would allow Fleet 1 trucks to be fully electrified (all measured routes) with a 1,500-kWh battery and 175-kW charge rate; Fleet 2 trucks could be fully electrified with a 1,375-kWh battery and 100-kW charge rate; and Fleet 3 trucks could be fully electrified with a 1,000-kWh battery and 300-kW charge rate.
>
> *Scenario 3:* Operational and technology changes that enable charging tractors when they are stopped for 10 minutes or more would allow Fleet 1 trucks to be fully electrified (all measured routes) with a 1,500-kWh battery and 150-kW charge rate; Fleet 2 trucks could be fully electrified with a 1,250-kWh battery and 350-kW charge rate; and Fleet 3 trucks could be fully electrified with a 900-kWh battery and 300-kW charge rate.

Full adoption of BETs could reduce carbon dioxide (CO_2) emissions from these fleets by roughly 75% today, eliminating 76 metric tons of CO_2 ($MTCO_2$) per truck each year, which equates to 24,100 $MTCO_2$ per year for all three operators.

Future Impacts to PoNYNJ

Commercially available DC fast chargers have charge rates up to 350 kW. Based on the average daily modeled energy use for each operator, current industrial rate structures, and the assumption of 350-kW peak charging, full drayage electrification would increase electricity consumption by the values shown in Table ES-1. In addition, peak demand usage would increase with unmanaged charging, along with cost of electricity having a direct impact on cost per mile for BETs. The resulting cost per mile for BETs, along with comparable cost per mile for conventional diesel trucks, are also shown in Table ES-1 with fuel at $4.00 per gallon of diesel.

Table ES-1. Operator Infrastructure Demands and Costs

Operator	Energy Use (MWh per month)	Demand (Peak MW)	Electric Price (¢/kWh)	Electric Cost Avg. ($/mi)	Fuel Cost Avg. ($/mi) for $4.00/gal
Fleet 1	1,226	3.5	11.9	0.333	0.858
Fleet 2	1,635	10.3	22.8	0.638	0.856
Fleet 3	2,776	10.8	15.5	0.434	0.709

It will be important for PANYNJ and the drayage operators within the PoNYNJ to consider these load impacts to their existing electrical infrastructure and devise operational strategies that avoid coincident charging of trucks to mitigate demand charges. Despite these electricity cost increases, savings from reductions in diesel consumption will help offset the costs of this increased electricity consumption. However, prices of both electricity and diesel are subject to change based on various factors, meaning the realized savings will vary over time. Table ES-2 provides a scenario analysis examining the dollar-per-mile savings from electrification at various prices for electricity and fuel.

This shows BETs could be cost-competitive on an energy-cost-per-mile basis for all scenarios while diesel is above $3.00/gal. Further, if diesel prices dropped to the 15-year low of $2.33/gal, it would still be cost-competitive to operate the BETs with electricity costs of $0.163/kWh or less.

Table ES-2. Dollar-per-Mile Savings from Electrification

Dollar-per-Mile Savings from Electrification [$/mi]

Fuel Price [$/gal] \ Electricity Price [$/kWh]	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
6.00	1.06	0.94	0.82	0.70	0.58	0.46	0.34	0.22	0.10
5.50	0.96	0.84	0.72	0.60	0.48	0.36	0.24	0.12	0.00
5.00	0.86	0.74	0.62	0.50	0.38	0.26	0.14	0.02	−0.10
4.50	0.76	0.64	0.52	0.40	0.28	0.16	0.04	−0.08	−0.20
4.00	0.66	0.54	0.42	0.30	0.18	0.06	−0.06	−0.18	−0.30
3.50	0.57	0.45	0.33	0.21	0.09	−0.03	−0.15	−0.27	−0.39
3.00	0.47	0.35	0.23	0.11	−0.01	−0.13	−0.25	−0.37	−0.49
2.50	0.37	0.25	0.13	0.01	−0.11	−0.23	−0.35	−0.47	−0.59
2.00	0.27	0.15	0.03	−0.09	−0.21	−0.33	−0.45	−0.57	−0.69

The following report provides details of the data collection, modeling, and analysis to support the conclusions summarized in this Executive Summary.

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1 Introduction

The National Renewable Energy Laboratory (NREL) provided technical assistance to the Port Authority of New York and New Jersey (PANYNJ) by providing input data to evaluate the potential for drayage truck electrification and analysis to inform future truck and infrastructure requirements. Using a suite of data acquisition, analysis, and visualization tools, NREL conducted real-world performance evaluations of drayage trucks from three Port of New York and New Jersey (PoNYNJ) operators. This report summarizes the data collection and electrification evaluation of the drayage truck operation that occurred from March to July 2021. Results from this project will provide detailed operational data and performance requirements of battery-electric trucks (BETs) operated within the context of the three drayage operations and highlight trucks that are candidates for electrification. The report will also provide a methodology to evaluate opportunities, strategies, and challenges associated with future expansion of BETs in the context of drayage operation.

Heavy-duty trucks are a substantial source of landside port carbon dioxide (CO_2) emissions in the PoNYNJ [1]. Further, drayage trucks have been shown to produce between 25%–43% of port-related nitrogen oxide (NO_x) emissions [2]. Vehicle electrification is an effective pathway for emissions reduction in freight applications [3, 4], and recent advances in BET technology have enabled multiple manufactures to develop electrified tractors. This study examines the potential for drayage electrification within the PoNYNJ and the corresponding emissions reduction as part of PANYNJ's goal to achieve net-zero carbon emissions by 2050 across all its facilities, including from tenant and stakeholder emission sources such as drayage trucks.

1.1 Data Collection

NREL subcontracted engineers from Energetics to install loggers on 46 diesel drayage trucks at three different operators. Specifically, a mix of ISAAC Instruments DRU900/908 (Figure 1 left) and Vector GL2000 (Figure 1 right) J1939 Controller Area Network (CAN) and GPS data loggers were installed on 12 trucks in Fleet 1, 9 trucks in Fleet 2, and 25 trucks in Fleet 3.

Figure 1. ISAAC data logger (left) and Vector GL2000 data logger (right).

Photos by Adam Ragatz (left) and Andrew Kotz (right)

Company-owned trucks were targeted for this study. A breakdown of the fleet composition and owner-reported mileage is shown in Table 1. Data were collected continuously over two 4-week periods from March to July 2021. Detailed performance data, including engine CAN and GPS information, were monitored at 1 Hz, generating over 30 million data points and 120,000 miles of data. High-level metrics are shown in Table 2.

Table 1. Truck Count by Operator

Operator	Trucks	Company Owned	Owner Operator	Daily Distance	Model Years
Fleet 1	58	16	42	300 mi	2018
Fleet 2	93	93	0	20% 50 mi, 80% 100 mi	2011, 2016
Fleet 3	165	30	135	80% 10 mi, 20% 150 mi	2009, 2016, 2017, 2019

Table 2. Data Collection Statistics

Miles of data	120,981
Gallons used	21,722
Hours of operation	10,443
Vehicle days	898

Maps of the truck GPS data for each operator are shown in Figure 2. for Fleet 1, Figure 3 for Fleet 2, and Figure 4 for Fleet 3, which show locations from each second of operation of each instrumented truck, highlighting the coverage of the studied trucks. Of note, the GPS traces of Fleet 2 show that trucks do not travel as far from port as those trucks in Fleets 1 and 3.

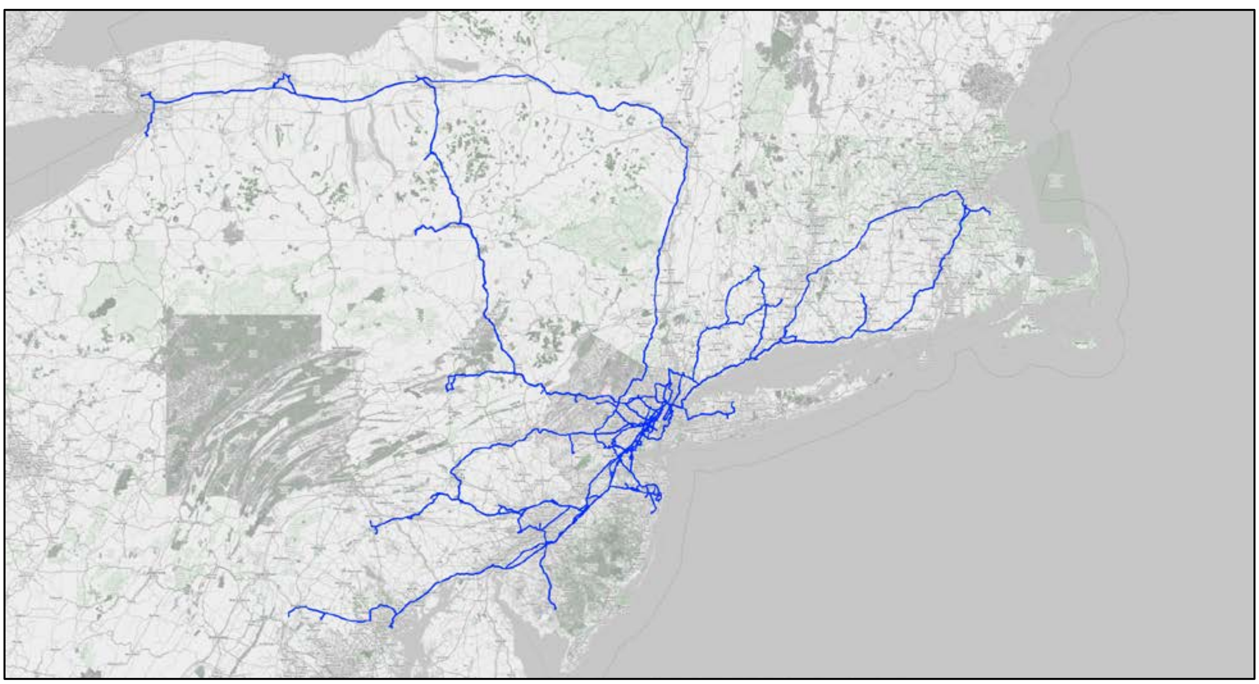

Figure 2. GPS trace of all collected Fleet 1 routes.

Source: Open Street Maps

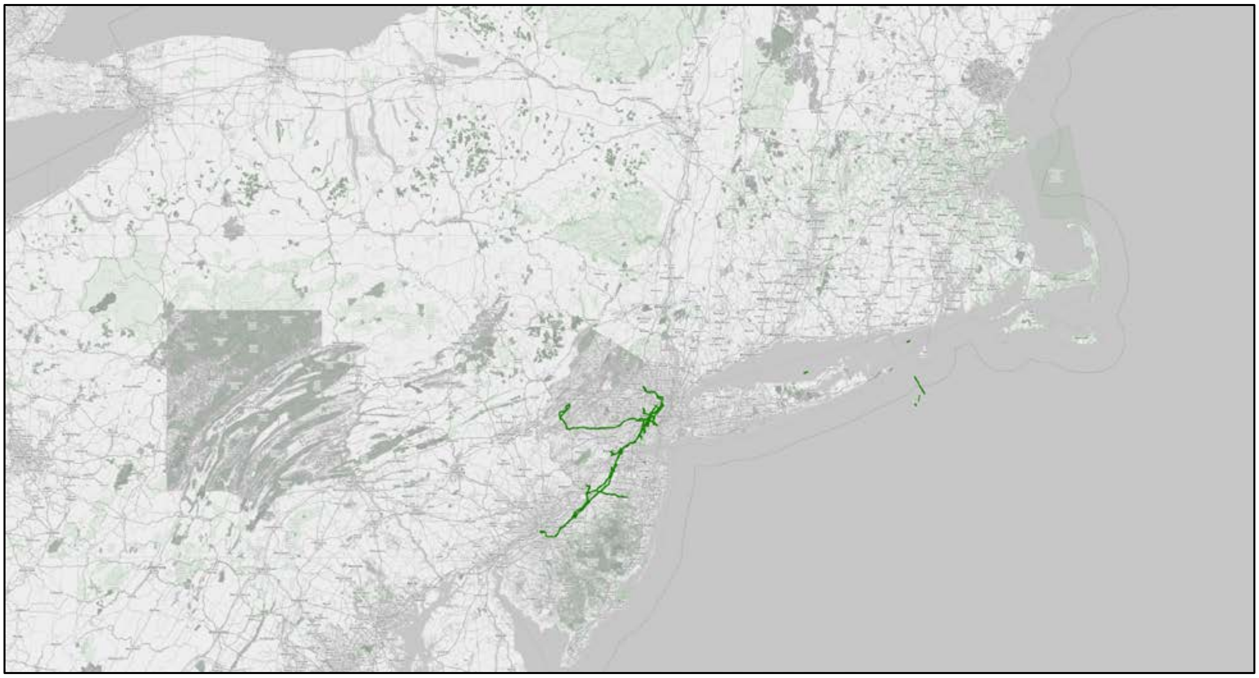

Figure 3. GPS trace of all collected Fleet 2 routes.

Source: Open Street Maps

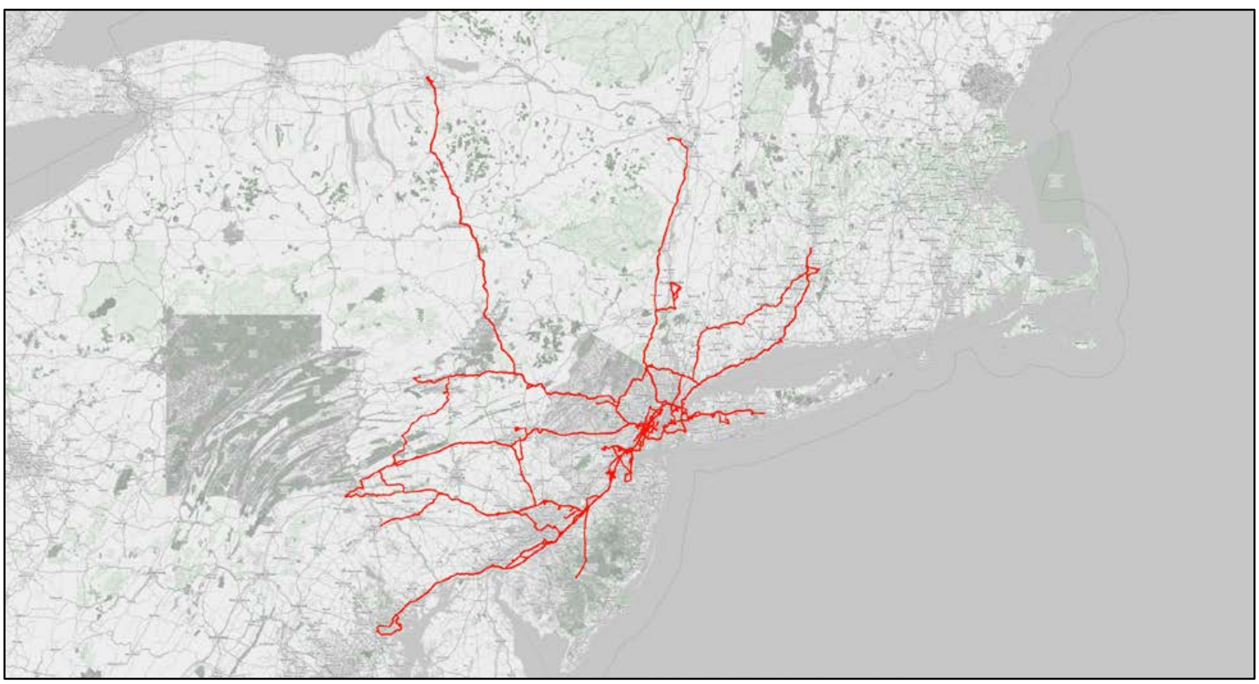

Figure 4. GPS trace of all collected Fleet 3 routes.

Source: Open Street Maps

2 Analysis

NREL's experience in evaluating, measuring, and verifying fleet deployments of advanced medium- and heavy-vehicle technologies has illustrated the relationship between vocational duty cycle, energy efficiency, and emissions, as well as the potential impacts on life cycle costs, barriers to implementation, and commercial viability [5–8]. This work has shown that knowledge of real-world port vehicle applications and drayage operation is critical in selecting the right technology for the given application, maximizing energy efficiency, and quantifying economic and performance impacts.

2.1 Duty Cycle

Understanding duty cycle is essential when evaluating a truck for electrification. Attributes such as average speed and daily distance are a first step in evaluating whether a duty cycle has characteristics conducive to electrification. For example, trucks with frequent speeds above 40 mph are more difficult to electrification, as they expend significant energy to overcome aerodynamic drag [9], which, unlike kinetic energy, is energy that cannot be recovered through regenerative braking. Distributions of daily average speed and distance from the studied trucks are shown in Figure 5. While the average daily distance of the drayage trucks was around 140 miles per day, there were some trucks that traveled over 570 miles per day. If BETs are expected to provide a one-to-one replacement for conventional trucks, they will need to accommodate the longest daily distance. The average daily driving speed was around 15 mph, but the maximum was around 60 mph, suggesting that some trucks consistently operate at high speeds while others have frequent stop and start operation. This is likely a result of waiting for loading and unloading of containers and other cargo; however, each drayage operator has slightly different operations, as shown in the operator-specific distributions in Figure 6.

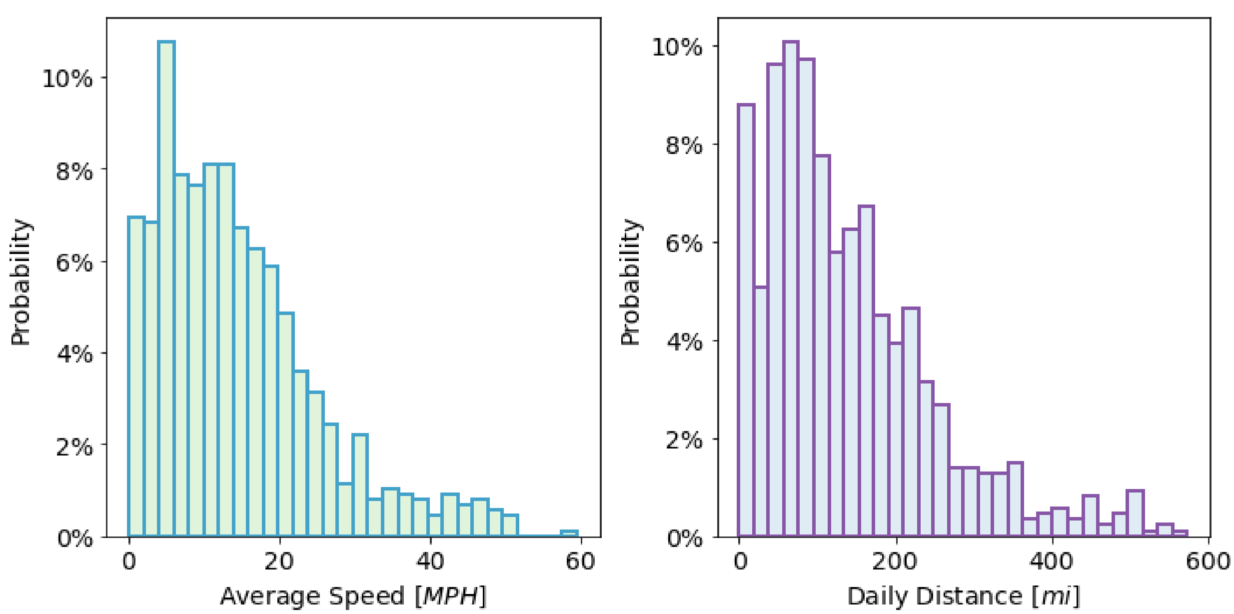

Figure 5. Distribution of daily average driving speed and distance

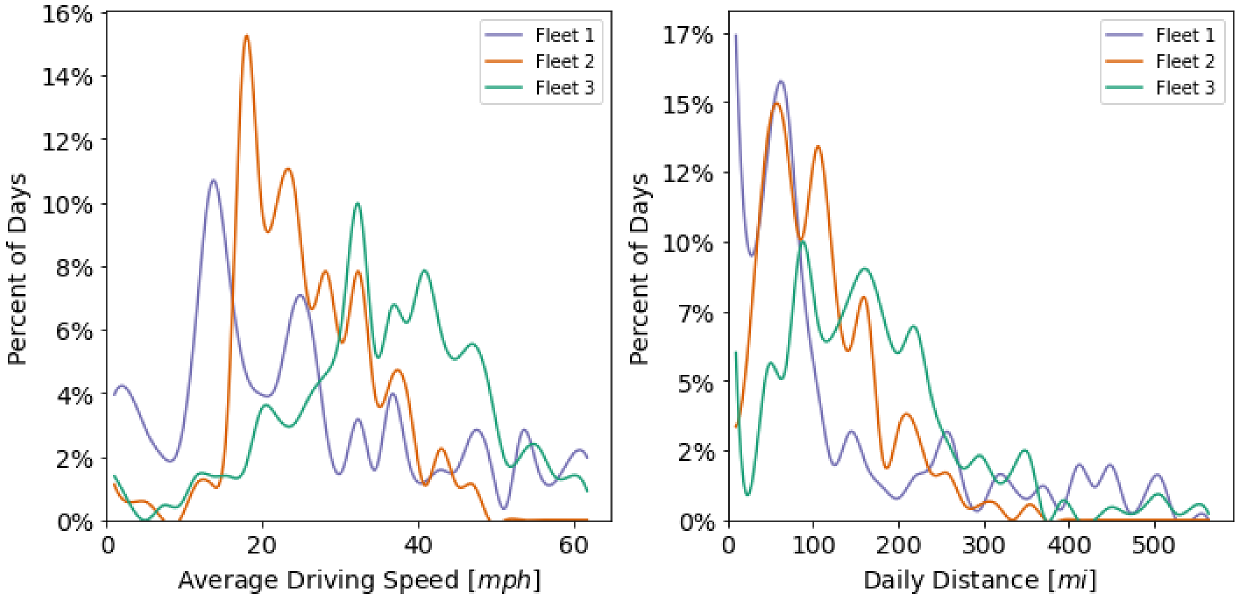

Figure 6. Operator-specific daily average driving speed and distance distribution

Fleet 2 has the lowest daily average distance at 106 mi, followed by Fleet 1 at 120 mi and then Fleet 3, which has the highest daily average distance at 165 miles. Based on its lower daily distances traveled, Fleet 2 trucks would be the first candidates for electrification; however, the maximum daily distance is 345 mi for Fleet 2, which is currently further than the projected range of existing BETs. The average daily fuel economy as measured from the CAN-reported fuel consumption was 5.4 miles per gallon (MPG) for the data collection period, which equates to 26 gallons of fuel per day on average at a rate of 2.7 gal/h. Distributions of both daily fuel economy and fuel consumption rates are provided in Figure 7, which includes data from all observed trucks, and Figure 8 shows the individual fuel economy and fuel rate distributions.

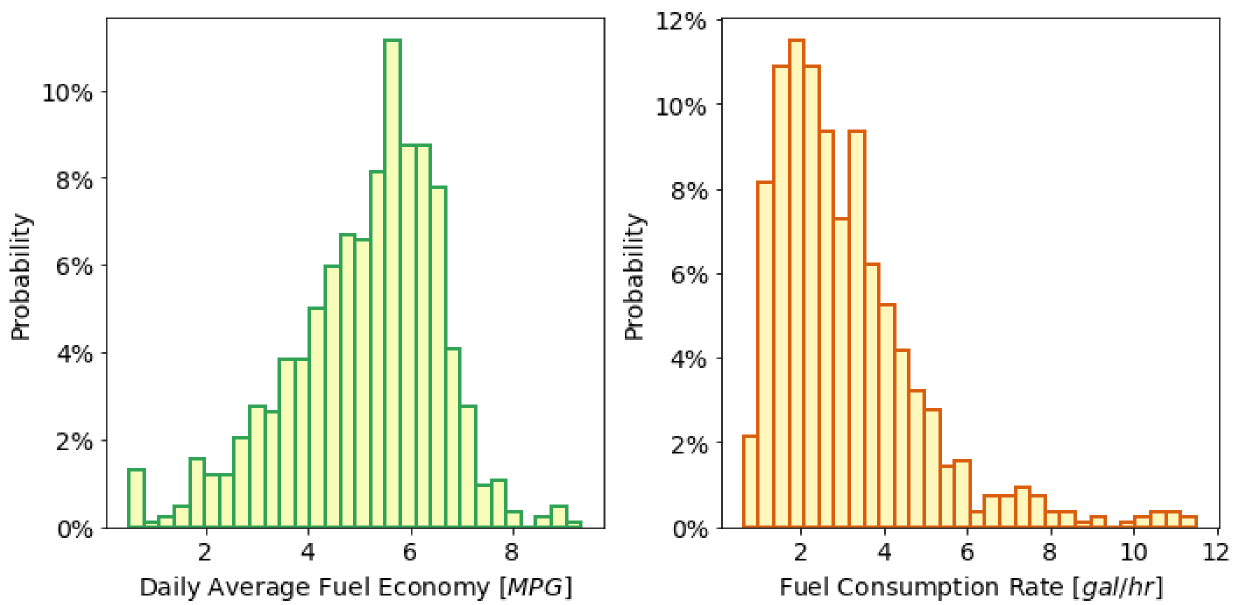

Figure 7. Daily average fuel economy and fuel consumption rate

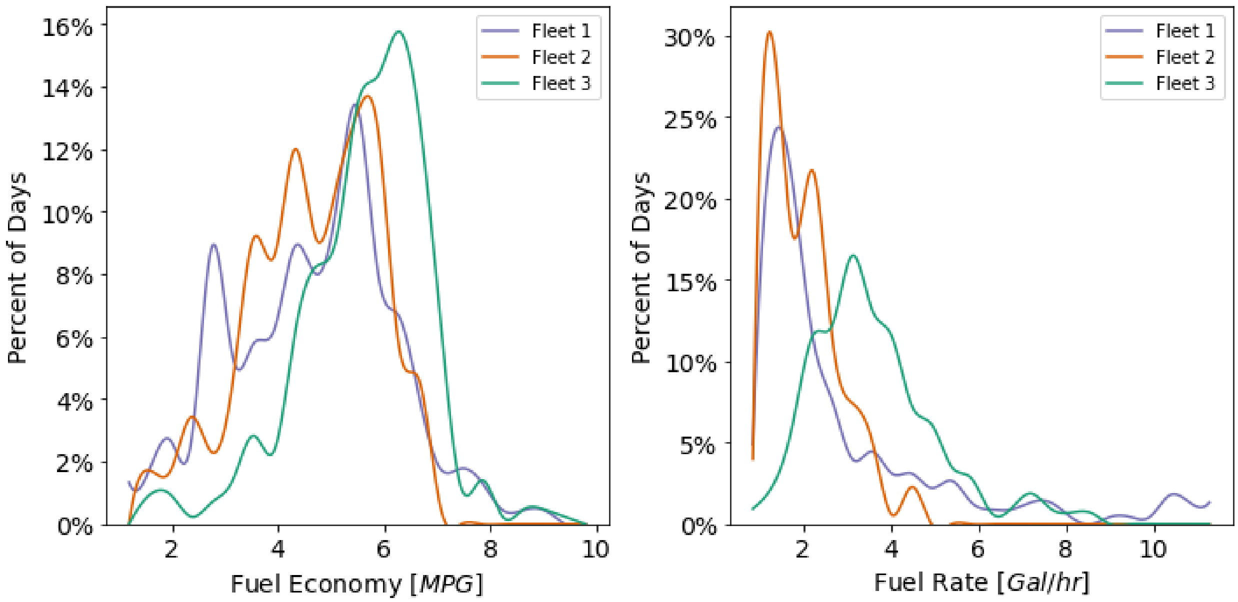

Figure 8. Operation-specific daily fuel economy and fuel rate distributions

Drayage trucks at Fleet 1 and Fleet 2 had similar distributions in fuel economy between 3 and 7 MPG with an average around 4.7 MPG, which shows a range of payloads and duty cycles. However, the daily average fuel economies for Fleet 3 have a narrower and higher distribution between 4 and 8 MPG with an average of 5.6 MPG. These fuel economy numbers are lower than tractor trailers in regional-haul operation, which average 8.3 MPG [10], suggesting Fleet 1 and Fleet 2 duty cycles have more energy-intensive operations such as stop-and-go driving or heavier loads.

BETs use very little, if any, energy when they are stopped. In contrast, conventional internal combustion engine trucks may use a significant amount of fuel and generate emissions while the engine is idling. Engine idling is defined as having the engine on while the truck is stationary (vehicle speed is zero). This can happen for brief periods at stoplights or for longer periods while waiting for containers or to enter marine terminals. Electrification can provide a substantial reduction in stationary energy use, depending on the truck drive cycle and requirements for operating accessories like air conditioning. However, if the truck has limited engine idling with the engine running for large portions of the day, there is limited opportunity to reduce stationary energy use and limited options for stationary charging, making the truck a poor candidate for electrification. Figure 9 shows the distributions of daily engine run time and the daily idle time. Drayage trucks in this study had an average engine run time of about 8.4 hours with a maximum daily run time of 17.3 hours. Further, based on results of this study, drayage trucks idle (engine on and vehicle stationary) an average of 4.4 hours per day and maximum of 12.5 hours per day combining all idle events. This provides a good opportunity for reducing energy use through electrification, as BETs do not have emissions and consume little or no energy while stationary, depending on the number of electric accessories. A deeper understanding of truck accessory loads such as HVAC, power steering, and air compressor use is required to fully understand this potential benefit.

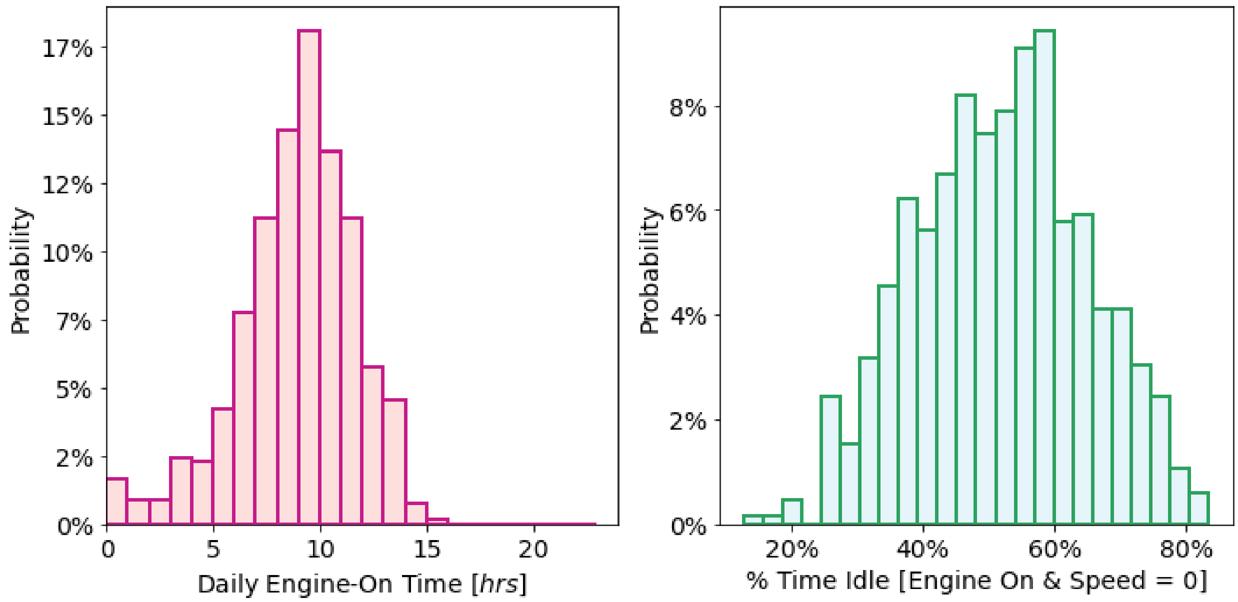

Figure 9. Daily average engine-on hours and engine idle hours

Individual distributions of daily engine-on time and idle fractions for each operation are shown in Figure 10. Fleet 1 has the highest engine run time with up to 17.3 hours of operation, and the other two fleets had up to 14.7 hours of operation, which is likely the result of a two-shift operation. However, all fleets averaged below 11 hours of operation each day, meaning there is potentially an opportunity for these trucks to charge if the truck off-time or dwell time is collocated with a charger. Further, between 20% and 80% of the operation is spent at idle (engine on and vehicle stationary), meaning there may be potential for opportunity charging during times when the truck would traditionally be idling, assuming they are collocated with charging infrastructure; however, further analysis is needed to determine idle locations.

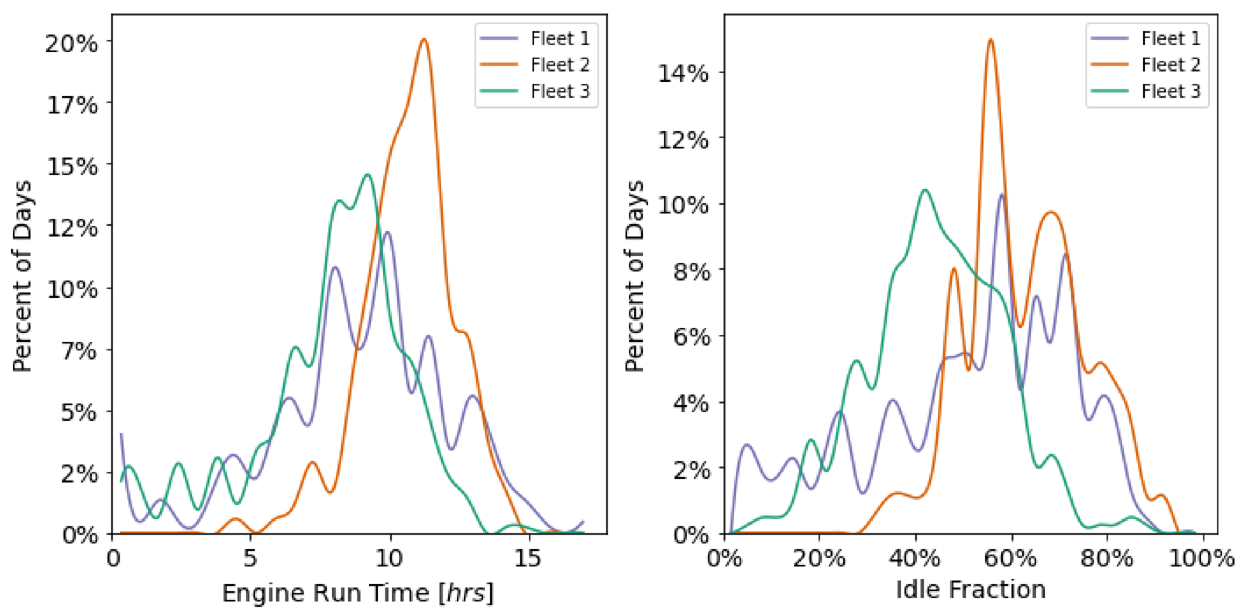

Figure 10. Operator-specific distribution of daily run time and engine idle

As of this report's writing, the largest commercially available battery capacity for an electric truck is 475 kWh usable energy (included on the Daimler eCascadia). Therefore, a candidate battery-electric duty cycle would have to use less energy than 475 kWh between charges, and a driver would likely not allow the battery state of charge (SOC) to drop to 0%. A more realistic battery range would be 375 kWh, which would give the driver a 100-kWh buffer. Other truck models exist with battery sizes ranging from the 375 kWh Volvo VNRe to the 753 kWh Nikola TRE tractors, however, the eCascadia was chosen at the time of modeling because one of the studied fleets had this truck on order. Despite choosing a single battery size for current technology, data on larger battery sizes is provided throughout this analysis to account for improvements in battery technologies and energy densities over time.

While energy use is highly dependent on the drivetrain, examining an existing truck's daily flywheel energy, or usable energy produced by the engine, is a good initial approximation providing the scale of the energy requirement of a comparable BET. Daily engine flywheel energy and percent of daily energy used at idle are shown in Figure 11. On average, the drayage trucks require 338 kWh of tractive energy per day, which is less than the 375 kWh of available battery-electric tractor driving energy. Further, the average daily idle (engine on and vehicle stationary) energy is 8.9% of total energy consumed, implying that, on average, 8.9% of the daily energy used would not be needed in a BET application, thus enabling more operation to be electrified; however, it is important to examine the full truck duty cycle to identify the charging opportunity.

Figure 12 provides further detail on the operator-specific daily flywheel energy and fraction of energy expended at idle. The average daily flywheel energy of Fleet 3 is the highest of the operators at 390 kWh per day. While this is below the available battery size, the average Fleet 3 day would use part of the 100-kWh buffer. Further, each operation had days with energy requirements higher than the available battery size. Fleet 2 had a maximum daily energy requirement of 829 kWh, Fleet 3 1,466 kWh, and Fleet 1 1,680 kWh, which would be infeasible to electrify with one charge per day or without substantial opportunity charging throughout the day. Despite these high energy requirements, partial fleet electrification may be possible when the full charge-discharge cycle of the truck is considered, ensuring enough time exists to replenish the daily energy consumed in a BET. Further, detailed truck modeling can provide better insight into battery-electric performance.

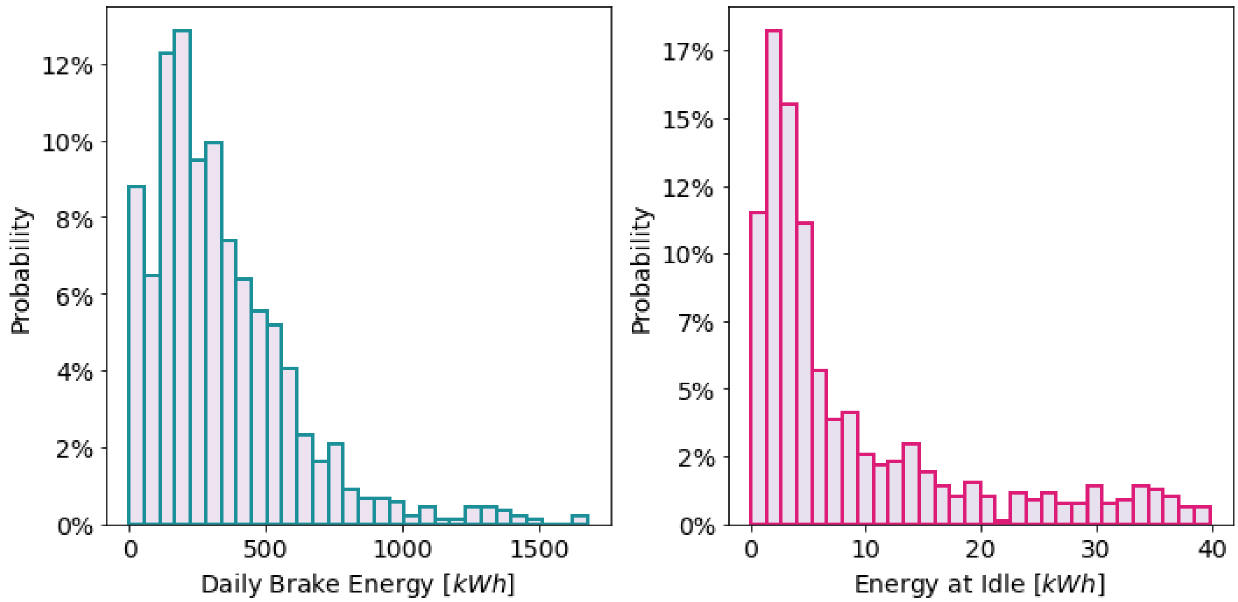

Figure 11. Daily average engine brake energy and percent of energy used at idle

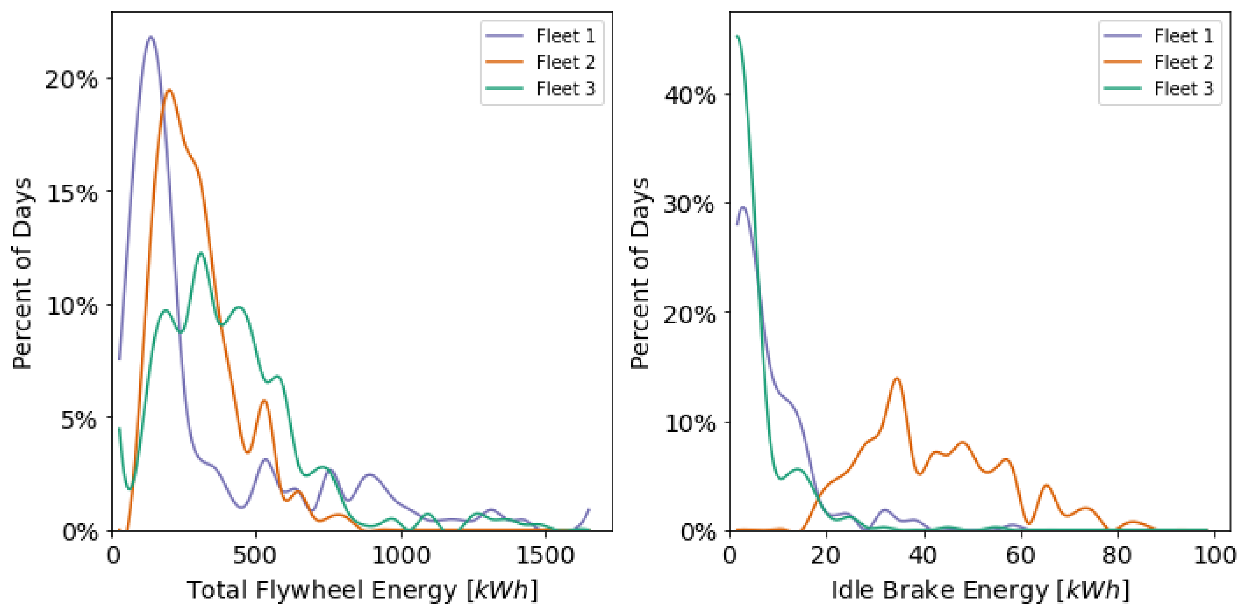

Figure 12. Operator-specific flywheel energy and fraction of energy spent at idle

2.2 FASTSim Truck Model

A model of an electric Class 8 heavy-duty truck was built in NREL's Future Automotive Systems Technology Simulator (FASTSim) to estimate the energy consumption of a BET undergoing the same drive cycles as the trucks for all the fleets as recorded by the data loggers. FASTSim is a physics-based, backward-looking model that estimates vehicle energy consumption, performance, and fuel economy using inputs such as mass, inertia, fuel converter parameters, air resistance, motor characteristics, battery specifications, tire dimensions, and other relevant vehicle characteristics. FASTSim balances model complexity with predictive accuracy and run time (Figure 13). Another important feature of FASTSim is its ability to account for energy recaptured through regenerative braking, which is a key component in the improved efficiency of BETs.

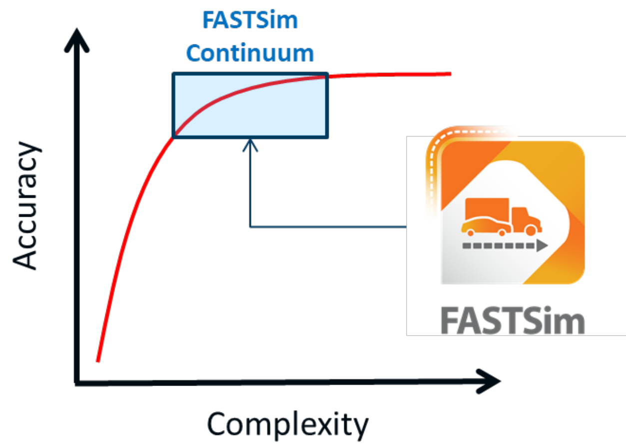

Figure 13. Conceptual illustration of the FASTSim domain on the vehicle modeling continuum

Source: Brooker et al. 2015 [11]

The parameters of the BET were determined in a previous effort [12] and provide a realistic representation of state-of-the-art commercial BETs on the road today. The BET model and accompanying analysis were carried out in two stages. First, the simplifying assumption is made that the mass of the truck is fixed for all trips at a conservative 60,000 lbs. This assumption enables an initial screening simulation to be run with reduced complexity that provides a conservative estimate of the BET energy for the recorded cycles in the logger data set. Additionally, the battery capacity of the BET is assumed to be unlimited, and therefore the BET can execute any drive cycle without recharging. This assumption was made to enable estimation of the BET energy requirements based on driving behavior alone. Table 3 shows some of the parameters used by the FASTSim model for calculating the BET performance. Other aspects of the study such as battery charge rate and charger location analysis include considerations of the more practical aspects and constraints of deploying a BET.

Table 3. Summary of BET Model Assumptions

Parameter	Value
Truck weight	60,000 lbs.
Drag coefficient	0.8
Frontal area	10.34 m^2
Motor power	300 kW
Battery power	500 kW

The second stage of the FASTSim model development involves the use of a mass estimation algorithm to adjust the truck mass for each trip. This is performed by using an optimization method to minimize the error per trip between the fuel consumption of the physical truck and the fuel consumption of a model of the truck (conventional truck model also built in FASTSim) with the mass as the decision variable. The form of the optimization problem is given by Equation 1:

Find $mass_{estimate}$, to minimize the fuel consumption error:

$$E_{fuel} = (fuel_{modeled}(D, \theta, mass_{estimate}) - fuel_{measured})^2 \tag{1}$$

Modeled fuel consumption is obtained from a FASTSim model simulating drive cycle D (speed, acceleration, road grade), with a set of truck parameters, θ, which are held constant, while the mass parameter, $mass_{estimate}$, of the truck model is varied minimize the fuel consumption error. This optimization problem is solved using the Nelder-Mead method. Constraints on the mass are applied to the optimization problem based on knowledge of the real conventional trucks. The lower and upper bound of the weight are 20,000 lbs. and 80,000 lbs., respectively. While many drayage operators have exceptions that allow them to operate with a weight limit of 115,500 lbs., the operators try not to exceed 88,000 lbs. and estimate this only occurs 5%–15% of the time; however, this use case was not modeled in this study.

The mass estimation algorithm integrated with the FASTSim workflow provides a finer resolution and more realistic estimation of the BET energy consumption for the same cycles implemented by the fleets. To account for the varying masses during trips due to different payloads, a mass estimation algorithm [13] was integrated into the FASTSim model as shown in Figure 14. The estimated accuracy of the algorithm is ±2,000 lbs.

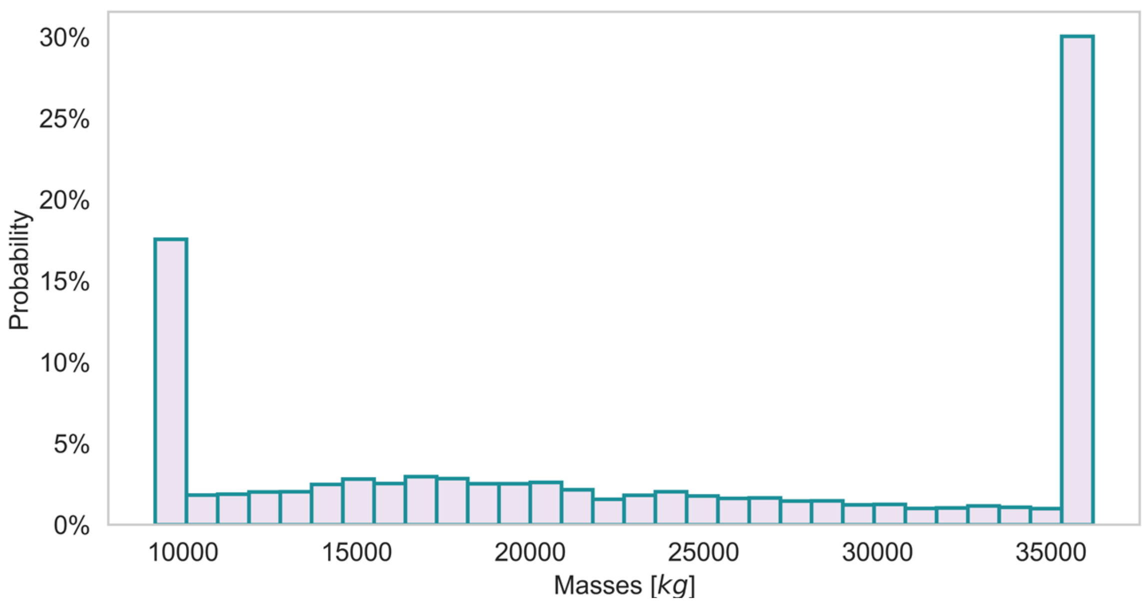

Figure 14. Distribution of predicted mass for each trip

Looking at total daily energy, Figure 15 shows the modeled BET energy use (right) along with the conventional diesel engine-produced energy (left). Results of the BET model are comparable to the diesel truck brake energy, providing confidence that the model is accurately assessing the truck's mass. Figure 16 shows modeled BET energy efficiency is around 2.4 kWh/mi on average, with the maximum daily consumption rate of 5.2 kWh/mi. Finally, Figure 17 provides the modeled daily energy recapture that would be expected from regenerative braking for all the trucks (left) and the individual fleets (right).

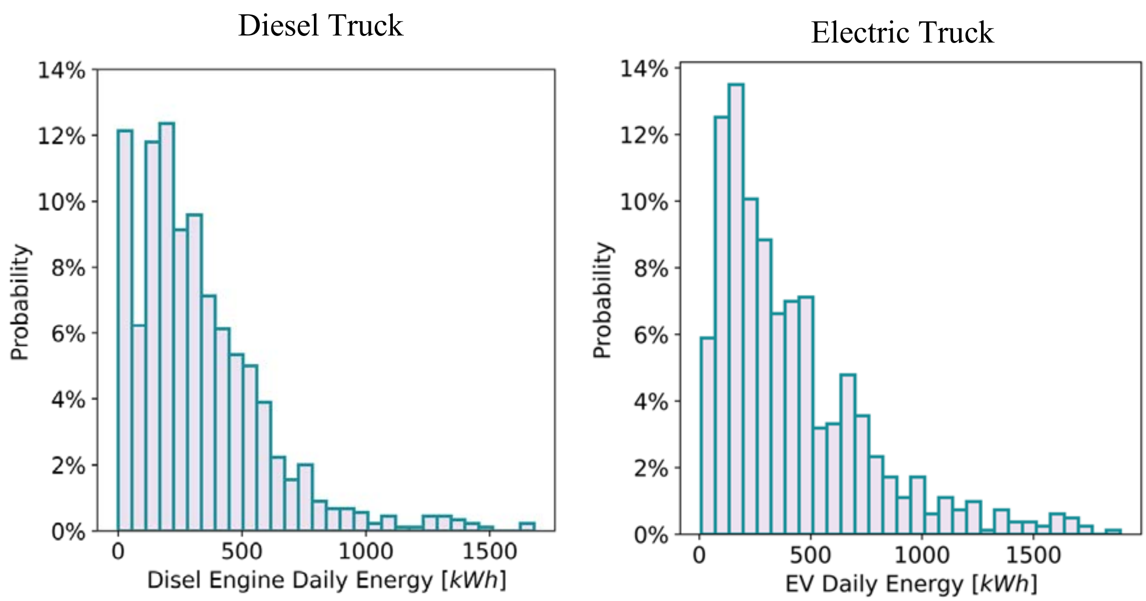

Figure 15. Energy use comparison between diesel and BETs (variable mass assumption)

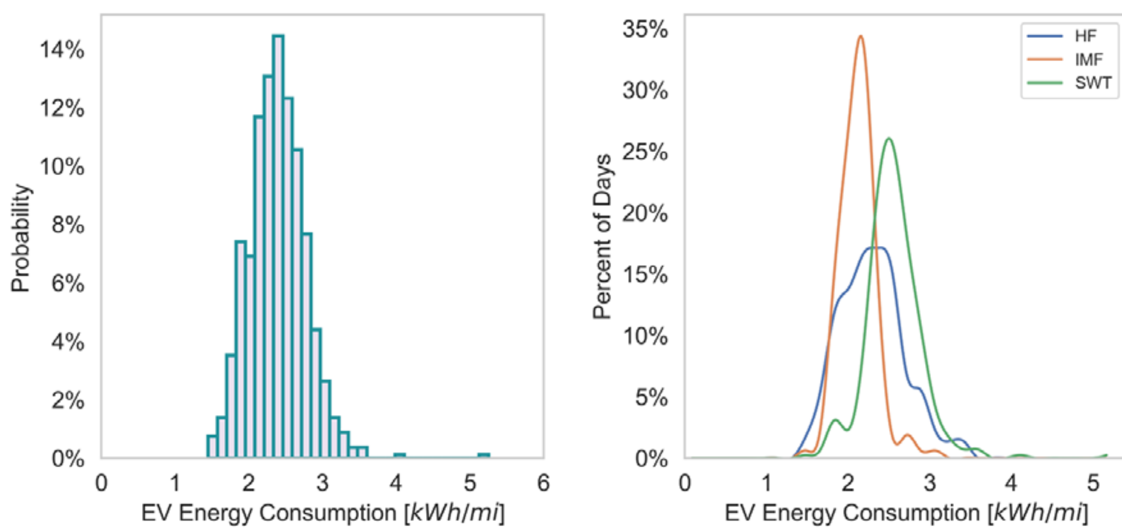

Figure 16. Energy use per mile combined (left) and for each fleet (right)

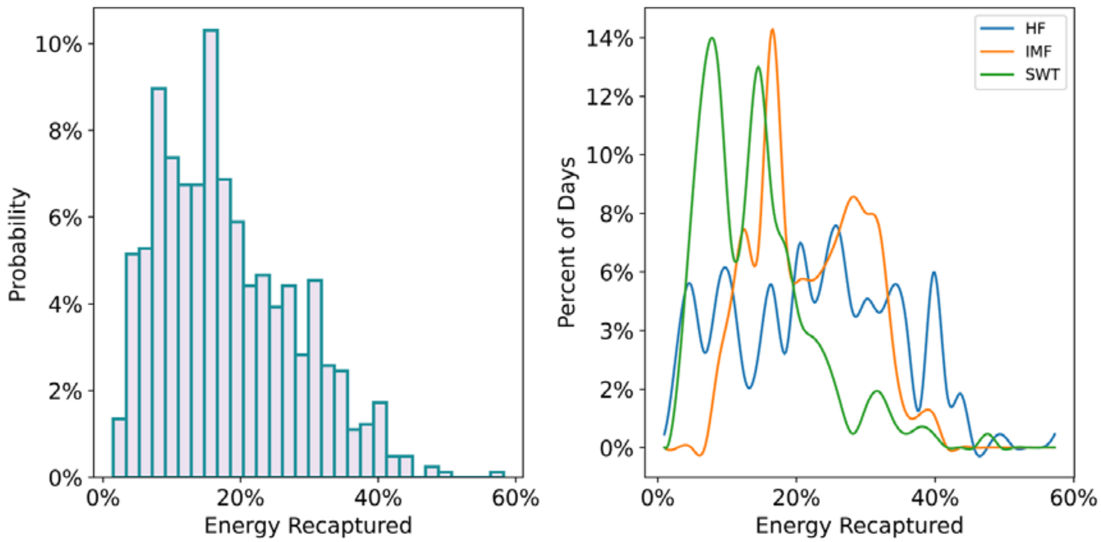

Figure 17. Estimation of modeled energy recapture

2.3 Charge Modeling

Charging is a key component to understanding the electrification potential of a fleet's operation. Traditionally, diesel tractors have fuel tanks large enough to complete multiple days of operation and can fill at rates of 30 gallons per minute. With diesel having approximately 37.6 kWh of energy per gallon [14], this is equivalent to charging an electric truck at 67 MW; however, the highest commercially available BET charge rates are 270 kW as of this writing. This is equivalent to adding roughly 135 miles per hour of charging for the BET, whereas a conventional diesel truck is adding over 200 miles of range per minute. Despite this vast discrepancy in charging/fueling rate, many trucks have sufficient downtime or dwell periods where the truck is not being used, such as overnight or on the weekends. These periods give the operator a chance to fully recharge the truck using lower power or slower charging to help reduce peak site loads. In addition to overnight charging, shorter periods throughout the day such as a lunch break or mandatory breaks during hours of service may provide enough time to add additional range using DC fast charging at higher powers, often called opportunity charging. Leveraging these different types of charging can enable broader fleet electrification.

Dwell count weighted by the maximum possible charge delivered for a given stop length is shown in Figure 18 to better illustrate the available charging opportunity in each interval bin. The weighting for each bin was equal to the stop duration times the charge rate of 270 kW up to the available battery size of 375 kWh, meaning after 1 hour, 23 minutes, the battery would be full if charged at 270 kW. However, it should be noted this assumption was only made for normalization purposes, and actual charge rate will vary based on battery chemistry and design. This weighting was then divided by the available battery size and number of trucks to provide a charge-weighted importance that avoids overcounting frequent short stops with limited charging potential and ensures long stops are not overemphasized once the battery is full.

There are frequent short stops less than 5 minutes shaded in red; however, these stops are not weighted heavily and do not provide enough time to gain meaningful charge when considering time to position, plug/unplug, and initiate charging of the truck. The next set of dwell periods ranging from 5 minutes to 1 hour, shaded in orange, could provide power to sustain the operation throughout the day if collocated with a high-powered charger. The last two sets of dwell bins are the slow charge shaded in green and the delayed charge shaded in blue, which are dwell times that are long enough that the trucks could use lower power levels to charge the trucks. The 1- to 10-hour slow charge bin has the fewest occurrences, meaning limited opportunity exists in this range; however, there is a distribution spike from 8 hours to 24 hours that could provide substantial opportunities for slow charging. Further, with the long dwell period, delayed or managed charging could be possible, allowing for trucks to be charged at further reduced charge rates or one after another to reduce peak demand. These events likely coincide with overnight parking events.

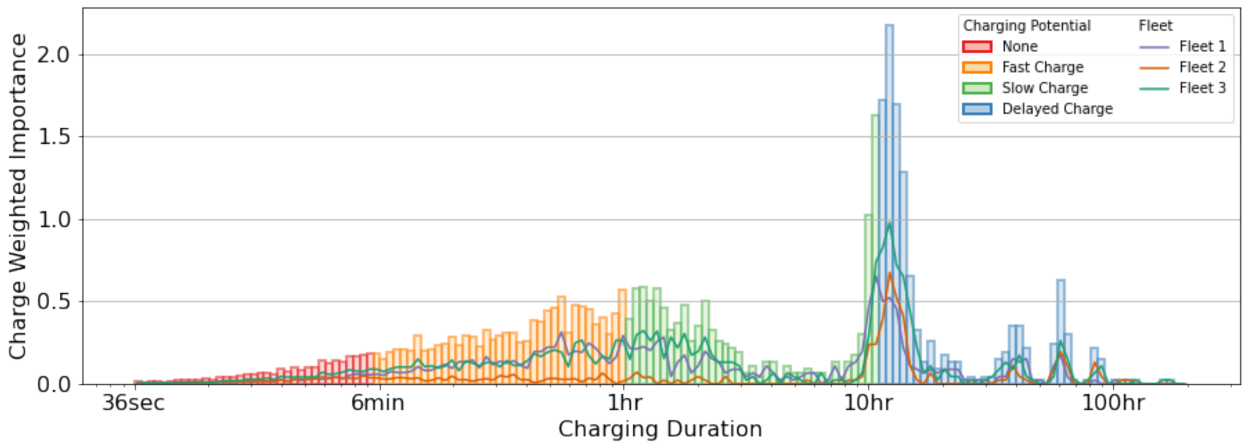

Figure 18. Logarithmic distribution of stop duration weighted by charge capacity

Location of dwell periods is another important consideration with charging to ensure the truck is near usable infrastructure. For instance, stops within the marine terminals are not feasible locations for installing charging, whereas the fleet home base would be an ideal location. A hotspot analysis was performed to identify charging locations (circled) based on how long trucks were stopped. Figure 19 shows the candidate locations, with frequent stop locations shaded in red with a valid location being where the truck was stopped for greater than 50 minutes. Larger and darker dots indicate more stop time. Identified stop locations are typically located at either warehouse loading docks, the operator's home facility, or within the marine terminal. Of the three locations, the operator's home facility is the most logical location to place chargers, as each operator has physical control over the facility. However, upgrades to electrical infrastructure may be needed to enable on-site charging for large numbers of BETs. Specifics of charging requirements are explored in Section 2.4. The other two locations are far more challenging to install charging infrastructure.

Warehouse loading docks are locations that trucks frequently stop at but are not controlled by the drayage operator or the PANYNJ. Therefore, the warehouse owner would be required to install this infrastructure, and there would be further logistical challenges of timing charging with unloading trucks as well as collocating chargers with the loading docks. Marine terminal charging has even more obstacles with the physical space limitations that require trucks to enter and leave as quickly as possible to facilitate timely container removal. Such requirements make charging at the marine terminal infeasible.

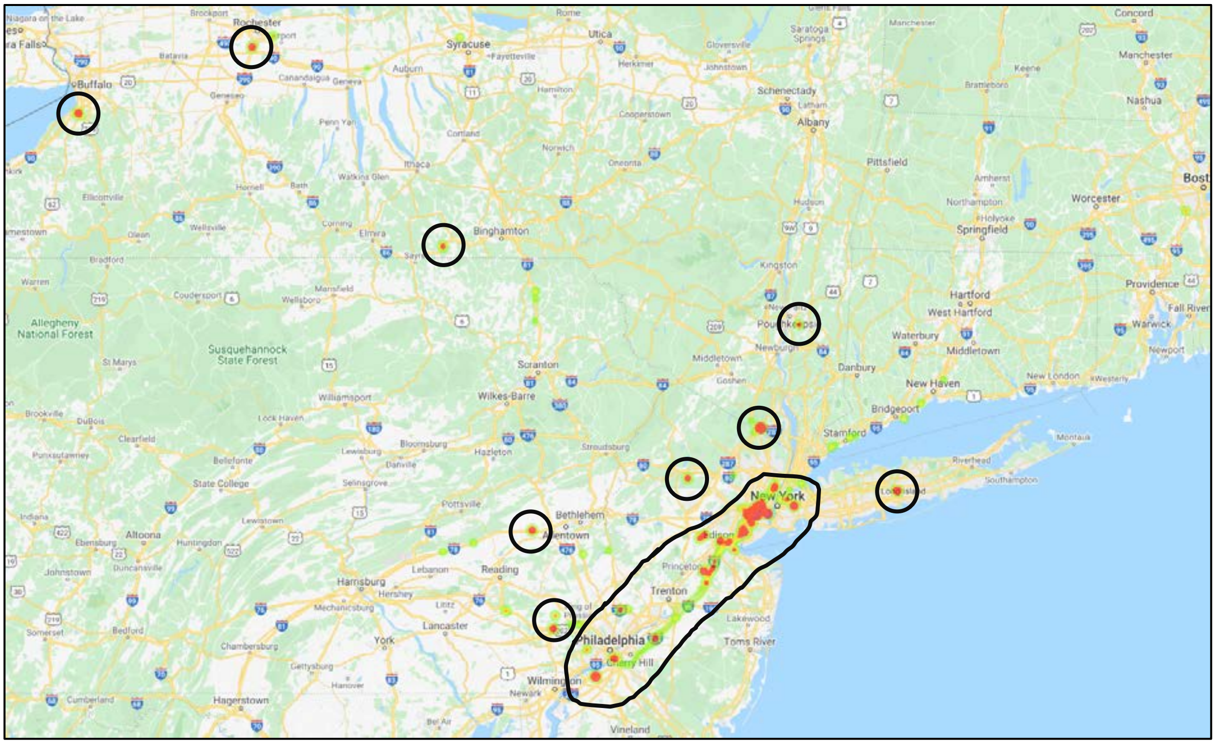

Figure 19. High-level charging hotspot analysis.

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Combining the usable dwell opportunities with the hotspot analysis, we examine the potential charging locations near the drayage operator facilities for four different dwell scenarios in Figure 20. The first scenario is the 1–2-hour dwell period in the top left of Figure 20, which shows multiple dwell opportunities within the operator facility boundaries. These stops could provide opportunity for fast charging or opportunity charging between trips. Figure 18 shows 1–2-hour dwell periods are relatively infrequent, yet they account for 4.4% of total dwell time and have events in the operator's facility where charging may be feasible. However, a substantial portion of these events happen within the container terminals, which are not feasible locations to charge.

The top right of Figure 20 shows 2–4-hour dwell periods, which is the next stop length examined. As expected, far fewer locations were identified, with no locations identified within the Fleet 2 facility. Despite the low location count, these stops could still provide valuable charging opportunities with the same infrastructure, as these dwell lengths make up 3.5% of total dwell time for 30-second to 24-hour dwell periods. A similar trend of fewer locations and no locations in the Fleet 2 facility are seen in the 4–8-hour dwell lengths (bottom left plot), which account for only 1.9% of total dwell time for 30-second to 24-hour dwell periods.

Overnight and delayed charging opportunities were the last dwell period types examined, encompassing dwell periods 8 to 24 hours in length, shown in the bottom right plot of Figure 20. This peak accounted for the largest fraction of dwell time for 30-second to 24-hour dwell periods, making up 79.8% of total time. Further, this timespan shows up in all operator facilities and has very few instances within the terminals, meaning managed slow charging at each operator facility is highly feasible. Further, if longer dwell periods that show up withing the container terminals could be relocated to the nearby operator facility, this could provide even greater charging availability.

Looking at the broader surrounding region in Figure 21, we see similar trends of having fewer hotspots with increasing dwell length, and longer dwell lengths disproportionately being located at operator facilities. However, one notable exception is circled to the lower left of the port, which is the diesel repair shop and would only be available for charging when the truck is in for service. While these analyses highlight opportune charge placement collocated with existing stops, it does not consider infrastructure improvement requirements that are likely needed to accommodate partial and full drayage electrification. Further, as public charging infrastructure for heavy-duty vehicles comes to fruition and battery technology improves, fewer on-site chargers may be needed at each operator facility. However, while charging and battery density limitations still exist, it is important to understand the route energy requirements in conjunction with the charging availability to capture the full charging requirement and truck design.

Figure 20. Hotspot locations for operator and terminal facilities

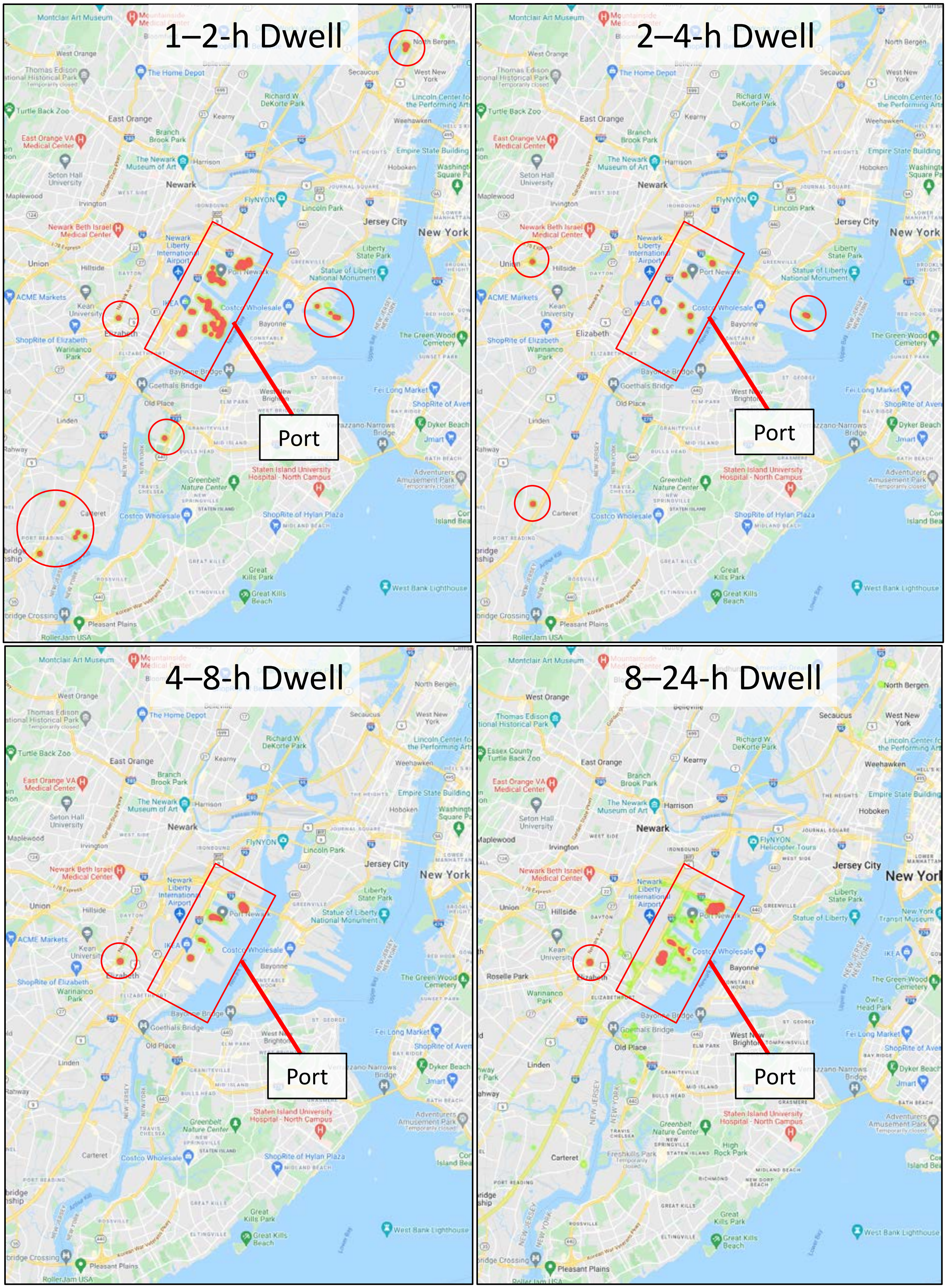

Figure 21. Hotspot locations for broader port region

2.4 Component Sizing

Using the truck model developed in Section 2.2, a flexible component sizing framework was developed to test different battery size and charge rate combinations against the required work and available dwell time. Each battery size and charge rate combination was run through every truck's operation to determine if that component configuration could successfully complete the operation without any SOC violation in which a truck runs out of energy. Figure 22 provides an example of the full SOC profile where the modeled truck accomplishes all days without any SOC violations. In this context, a SOC violation means that the truck needed more energy than available with the modeled battery size and charging rate. Reductions in SOC are associated with the modeled electric tractor performing tasks consistent with real-world operation and increases in SOC are from charging. The yellow line represents an SOC of zero, meaning that the battery is empty. In this instance, the plotted SOC represents truck activity for which a BET may be a suitable candidate, as it does not fall below the 20% line on any modeled vehicle days.

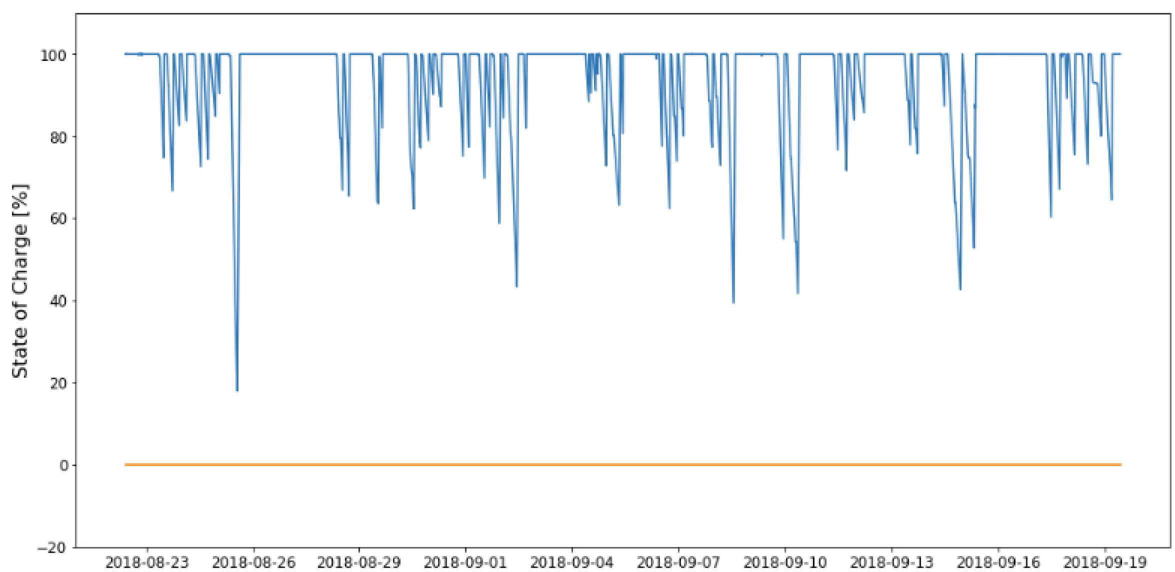

Figure 22. BET model that completes daily operation

While the truck in Figure 22 was able to perform its duty cycle without going below 20% SOC, Figure 23 provides an example of a truck duty cycle with an SOC violation. This is due to more aggressive use, prolonged periods of activity, and minimal charging opportunities.

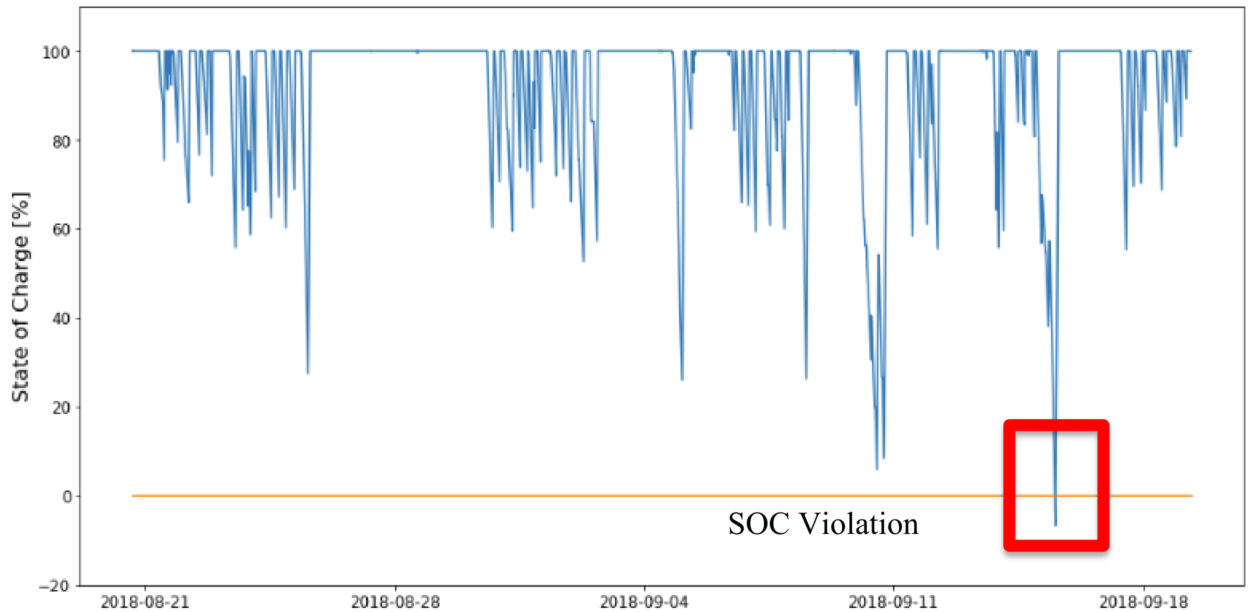

Figure 23. BET model with an SOC violation

Using this truck modeling framework, we explore the range of battery-electric tractor parameters to identify battery size and charge rates that can meet the full duty cycle for all trucks and better understand the relationship between tractor performance and component specifications. Figures 24, 25, and 26 show the number of SOC violations or failures in response to a sweep of input parameters for each operation. For Figure 24, which shows BET viability when trucks can charge when they are stopped for 2 hours or longer, battery size is shown to be the strongest predictor of successful tractor electrification, with no change in BET viability with charge rates over 200 kW. The Freightliner eCascadia is currently available with a 375-kWh battery size (usable) and 270-kW (nominal) charge rate and is shown with a pink dot in the figure. With these charge rate and battery size specifications and the assumption that the trucks can charge when stopped for 2 hours or longer, 9 of the 43 studied trucks could be electrified without modifying operation or rerouting trucks to accommodate BETs on more routes. Figure A-1 in the appendix shows the individual fleet BET viability plots for the 2-hour stop assumption, indicating 4 of 9 studied Fleet 2 trucks, 4 of 12 Fleet 1 trucks, and 1 of 22 Fleet 3 trucks could be electrified by only charging at stops of 2 hours or longer. This suggests that the Fleet 2 duty cycle is more conducive to electrification than the other two fleets, which makes sense since it had the lowest average daily distance of the fleets.

Outside of increasing battery size and charge rate, allowing the trucks to charge when stopped for shorter periods of time is another key tool for increasing BET viability. Figure 25 shows the BET viability analysis that assumes trucks can charge when stopped for 50 minutes or longer. While BET viability is still insensitive to charge rates over 200 kW with current battery sizes, we start to see increased BET viability with higher charge rates for the 750-kWh and 900-kWh battery size should this technology become available. Using available technology for the 50-minute scenario, 15 of the 43 studied trucks could be electrified. Figure A-2 in the appendix shows the individual fleet BET viability plots for the 50-minute stop assumption indicating 5 of 9 studied Fleet 2 trucks, 4 of 12 Fleet 1 trucks, and 3 of 22 Fleet 3 trucks could be electrified by only charging at stops of 50 minutes or longer.

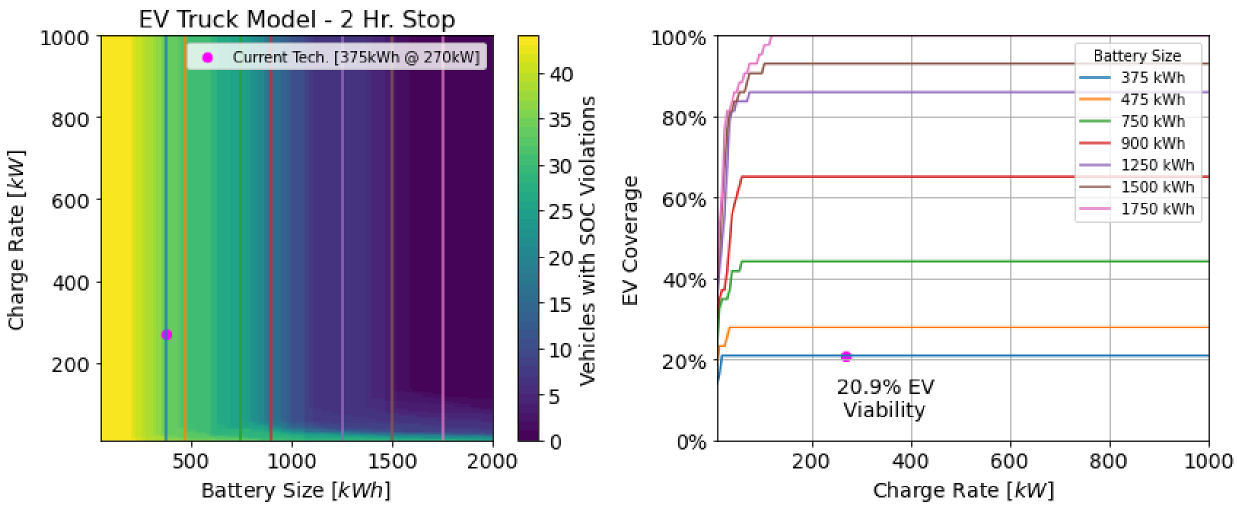

Figure 24. BET viability vs. charge rate and battery size for ≥2-hour dwell periods

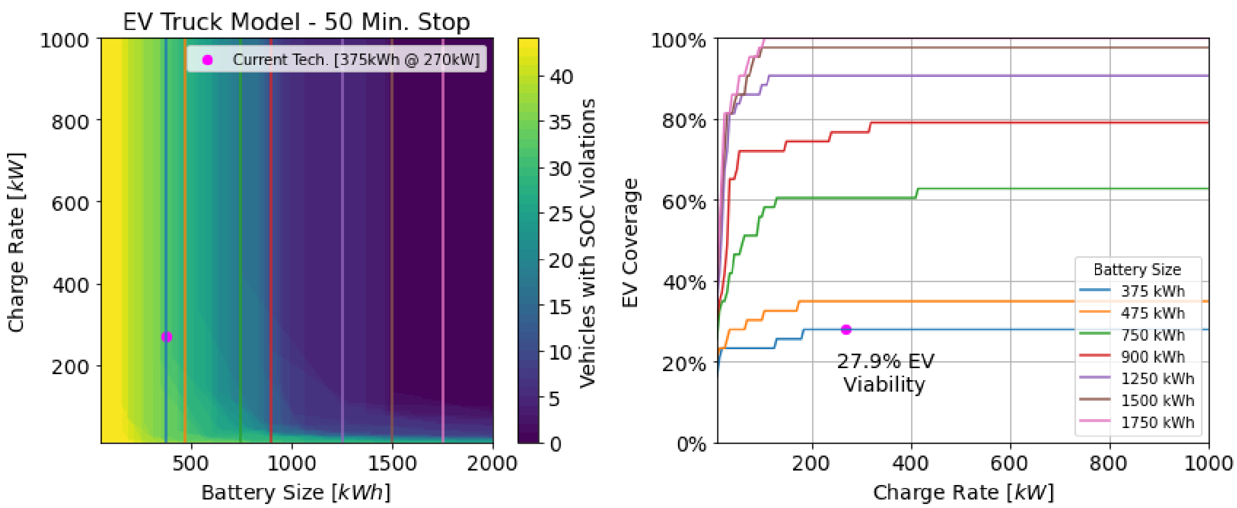

Figure 25. BET viability vs. charge rate and battery size for ≥50-min. dwell periods

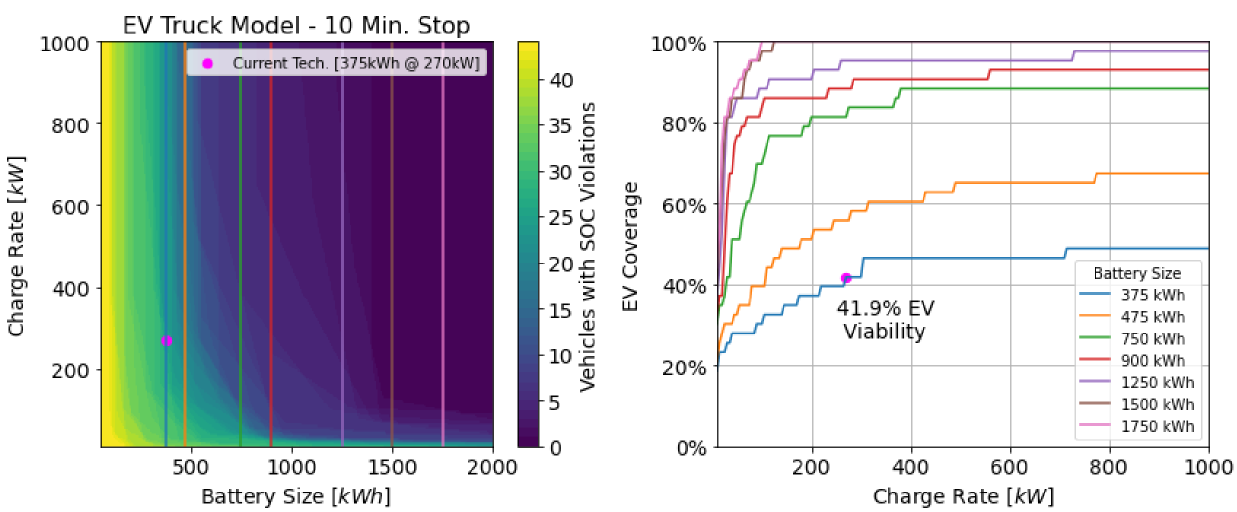

Figure 26. BET viability vs. charge rate and battery size for ≥10-min. dwell periods

Increasing BET viability by charging when the trucks were stopped for 10 minutes or more was the last scenario examined, shown in Figure 26. While this scenario is not feasible today, such a scenario can provide insight into electrification potential with future broad availability of charging infrastructure, including wireless charging and charging at customer locations. Based on this scenario, 24 of the 43 trucks show the ability to be electrified with existing battery size and charge rate scenarios. Figure A-3 in the appendix shows the individual fleet BET viability plots for the 10-minute stop assumption indicating 7 of 9 studied Fleet 2 trucks, 4 of 12 Fleet 1 trucks, and 7 of 22 Fleet 3 trucks could be electrified by charging at stops of 10 minutes or longer. In addition, we see scenarios of 100% electrification when both battery size and charge rate increase, indicating that advancements in battery capacity, charge rates, public infrastructure, and opportunity charging all play key roles in improving BET viability.

Finally, this analysis solely examines the operation as it is and does not rearrange trips or increase fleet size. If the desire exists to electrify a fleet, switching out trucks based on battery SOC could provide more opportunity to increase electrified miles. Finally, for fleets making frequent short trips, adding more trucks is an option, but will not provide a 1:1 fleet transition. However, with rapidly advancing technology, additional trucks may only be a temporary need.

2.5 Electricity Costs

Electricity is a key cost when operating an electrified fleet that displaces fuel costs when switching from internal combustion engine trucks. Overall cost of electricity is based on both the quantity of electricity used in kilowatt-hours and the peak power usage in kilowatts. Table 4 shows the existing monthly energy use, peak demand, and overall bill cost range for each operator except for Fleet 2, which NREL was not able to obtain utility information from. This analysis identifies the electricity costs and increase in monthly energy from electrification.

Table 4. Existing Operator Energy Usage and Peak Demand

Operator	Monthly Energy Usage	Monthly Demand	Monthly Cost
Fleet 1	22,000–44,500 kWh	67–86 kW	$3,000–$4,700
Fleet 3	3,000–5,000 kWh	12–17 kW	$470–$650
Fleet 2	-	-	-

Both fleets are under the Public Service Electric and Gas Company (PSE&G) General Lighting and Power rate, which covers commercial customers under 150-kW peak demand. However, depending on charger type, these trucks can charge between 120 kW and 350 kW, which would put the facility into the Large Power and Lighting Service rate for industrial customers. This change in rate structure shifts most of the cost from the energy use (kilowatt-hours used) to the peak demand (maximum monthly kilowatts).

Prior to evaluating the electricity requirements and costs, a few assumptions were made on how we measure monthly energy and peak power with each truck using different amounts throughout the month. The first assumption is that today’s rate structures will apply once the trucks are electrified. Electricity price depends on various external market factors that can either increase or decrease the overall cost for electricity; however, exploring those is outside the scope of this project, and this analysis focuses solely on current rate structures.

Next, there are two possible charging scenarios. The first is that only stops within the operator's facility are considered as opportunities to charge, and the second is that both stops within the operator's facility and near the marine terminal—which could possibly be relocated to the operator's facility nearby—are considered. Additionally, there are two possible energy use scenarios. The first scenario considers that all energy is provided by the operator-controlled charging and any charge not fulfilled in one charging session is rolled over to the next charge. The second scenario is that only the energy used in the previous trip is considered for the given charging event and any other energy is charged at another facility not controlled by the operator. The combination of the two possible charging scenarios and energy use scenarios results in the following four analysis scenarios:

1. Operator Charging Only | Only Last Trip's Energy
2. Operator Charging Only | Energy Rollover
3. Operator & Near Port Charging | Only Last Trip's Energy
4. Operator & Near Port Charging | Energy Rollover

Of the four available analysis scenarios, Option 2 is the least flexible and Option 3 is the most flexible. Therefore, these two scenarios were selected for this study. It is also assumed that a truck will charge at the lowest possible power and up to the specified charge rate for a given dwell period to reduce peak power demands. Monthly energy use per truck is shown for each option in Figure 27. Each fleet is shown individually, along with a combined scenario with all studied trucks labeled as "All" in the plot legend. Option 3 (left) shows far less energy use than Option 2 (right), and as charge rate increases the energy use increases. This indicates that not all charging needs are met under Option 3 and charging outside the port must be utilized. Conversely, Option 2 has a flattening curve with increasing charge rate, indicating maximum energy use is replenished under this scenario.

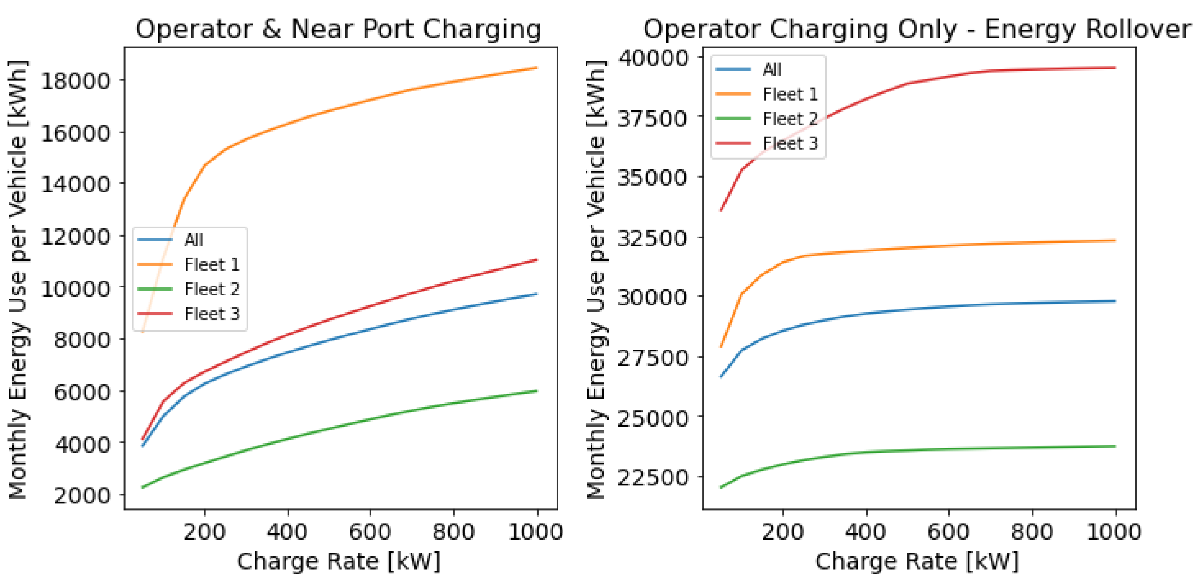

Figure 27. Monthly electricity usage under two charging scenarios

Finally, the main purpose of this effort is to identify the consequences of electrification at a broad scale, and since loggers were not placed on every truck in the fleet, output results must be scaled based on collected data. To do so, we assume that each truck within a fleet is the average truck for that fleet. To make this assumption, all collected truck data are compiled, and the average energy use and average charging power are taken for each second of data based on the number of trucks having loggers on at that given time. Those data are then assembled into the average weekday power profile and average weekend power profile and multiplied by the respective number of days in each month of the year. The cost is then calculated by adding the cost of electricity and the cost of the peak demand of the average truck, resulting in the monthly electricity bill for each charging scenario as shown in Figure 28. The resulting monthly bill for the Operator & Near Port Charging scenario that assumes charging can happen outside the operator facility (left) is expectedly less than that of the scenario that assumes all charging happens withing the operator facility (right), since less overall energy is provided to the trucks by the operator's facility under the left scenario. In addition, as the charge rate increases, the overall cost increases because of more energy throughput for the same charging duration. Conversely, the scenario shown in the right plot has electricity costs stagnating once a certain charge rate is achieved, suggesting that energy demands are met and increasing the charge rate will have little effect on the monthly cost.

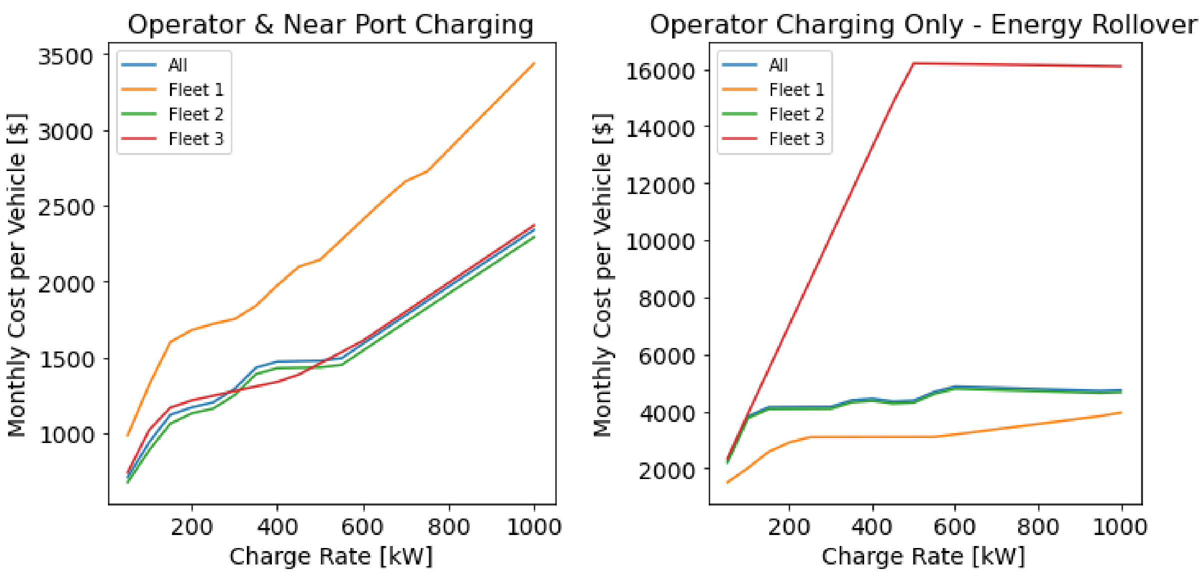

Figure 28. Monthly site electricity costs under two charging scenarios

Using these results, we can then compare electricity use to that of the existing utility bill to understand the increases in utility costs. Based on available technology, a 350-kW charger is used to charge the trucks, and cost scenarios for the baseline energy costs, costs with one truck added, and monthly energy costs for full fleet electrification are developed in Table 5. Results show that adding a single truck will increase the monthly electricity bill by 72% to 850%. With full fleet electrification, the cost to charge the trucks dwarfs that of the existing buildings and increases the utility bill between 21 and 2,100 times the current cost, depending on the facility and charging scenario. However, these costs could be supplanted with on-site generation or behind-the-meter storage and will be offset with the reductions in fuel use.

Table 5. Electrification Truck Energy Usage and Costs

Harbor Freight			
Scenario	**Monthly Energy Usage**	**Monthly Demand**	**Monthly Cost**
Facilities	22,000–44,500 kWh	67–86 kW	$3,000–$4,700
Single truck	16,000–31,800 kWh	41–75 kW	$1,800–$3,100
Whole fleet	927,300–1,845,900 kWh	2,361–4,340 kW	$106,600–$179,800

Safeway Transportation			
Scenario	**Monthly Energy Usage**	**Monthly Demand**	**Monthly Cost**
Facilities	3,000–5,000 kWh	12–17 kW	$470–$650
Single truck	7,800–37,800 kWh	27–350 kW	$1,300–$11,700
Whole fleet	1,288,700–6,242,700 kWh	4,446–57,750 kW	$215,600–$1,932,284

International Motor Freight			
Scenario	**Monthly Energy Usage**	**Monthly Demand**	**Monthly Cost**
Facilities	-	-	-
Single truck	3,900–23,400 kWh	31–117 kW	$1,400–$4,300
Whole fleet	362,800–2,175,900 kWh	2,902–10,926 kW	$129,100–$401,300

Despite the increase in the utility bill, these costs are offset by the reduction in diesel prices. With many factors influencing the price of both electricity and diesel, a range of conditions must be explored to understand the trade-offs when prices fluctuate. Combining monthly energy use with monthly cost, Figure 29 shows the price per kilowatt-hour, which ranges from $0.05/kWh up to $0.42/kWh based on charge rate. However, the national average is around $0.14/kWh [15], which is close to the current average for the fleets of $0.117/kWh to $0.155/kWh.

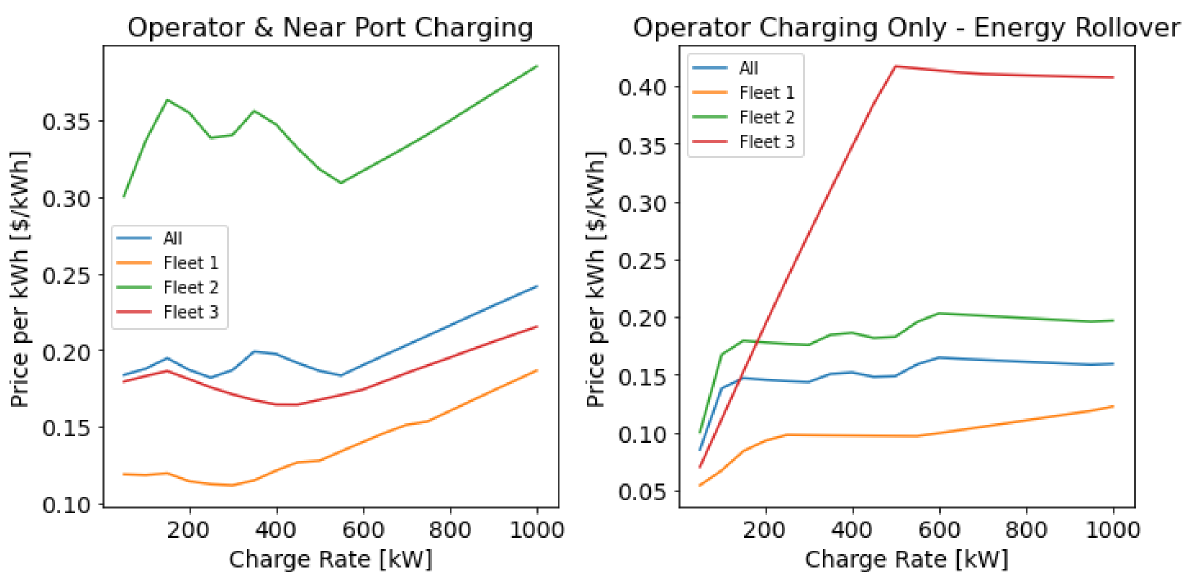

Figure 29. Electricity price under two charging scenarios

Likewise, diesel has had a yearly average range in price between $2.33 and $4.01/gallon over the last 17 years [16], with today's prices over $5.30/gallon [17]. Commercially available DC fast chargers have charge rates up to 350 kW. Based on the average daily modeled energy use for each operator, current industrial rate structures, and the assumption of 350-kW peak charging, full drayage electrification would increase electricity consumption by the values shown in Table 6. In addition, peak demand usage would increase with unmanaged charging, along with cost of electricity having a direct impact on cost per mile for BETs. The resulting cost per mile for BETs along with comparable cost per mile for conventional diesel trucks are also shown in Table 6 with fuel at $4.00 per gallon of diesel.

Table 6. Operator Infrastructure Demands and Costs

Operator	Energy Use (MWh/month)	Demand (Peak MW)	Electricity Price (¢/kWh)	Electricity Cost Avg. ($/mi)	Fuel Cost Avg. ($/mi) for $4.00/gal
Fleet 1	1,226	3.5	11.9	0.333	0.858
Fleet 2	1,635	10.3	22.8	0.638	0.856
Fleet 3	2,776	10.8	15.5	0.434	0.709

Looking at the comparative cost of energy source to understand the cost shift from diesel to electricity, Table 7 shows the dollar-per-mile savings from electrification for various diesel prices and electricity costs using the average BET energy efficiency of 2.4 kWh/mi and the average truck fuel economy of 5.1 MPG.

Table 7. Dollar-per-Mile Savings from Electrification

Dollar-per-Mile Savings from Electrification [$/mi]

Fuel Price [$/gal] \ Electricity Price [$/kWh]	0.05	0.10	0.15	0.20	0.25	0.30	0.35	0.40	0.45
6.00	1.06	0.94	0.82	0.70	0.58	0.46	0.34	0.22	0.10
5.50	0.96	0.84	0.72	0.60	0.48	0.36	0.24	0.12	0.00
5.00	0.86	0.74	0.62	0.50	0.38	0.26	0.14	0.02	−0.10
4.50	0.76	0.64	0.52	0.40	0.28	0.16	0.04	−0.08	−0.20
4.00	0.66	0.54	0.42	0.30	0.18	0.06	−0.06	−0.18	−0.30
3.50	0.57	0.45	0.33	0.21	0.09	−0.03	−0.15	−0.27	−0.39
3.00	0.47	0.35	0.23	0.11	−0.01	−0.13	−0.25	−0.37	−0.49
2.50	0.37	0.25	0.13	0.01	−0.11	−0.23	−0.35	−0.47	−0.59
2.00	0.27	0.15	0.03	−0.09	−0.21	−0.33	−0.45	−0.57	−0.69

At the current electricity price of $0.15/kWh and last year's diesel price of $3.50/gallon, the fleets will save $0.33 per mile. This savings diminishes as electricity price increases to $0.30/kWh, where it reaches cost parity with $3.50/gallon of diesel. However, with today's prices near $5.50/gallon, price parity is reached closer to $0.45/kWh. This shows that depending on the resulting electricity price structure and cost of diesel, the resulting electrification cost benefit may be diminished or even result in higher costs. However, despite the high projected electricity costs shown in Figure 29, it is possible that new BET rate structures will emerge with higher BET penetration to help incentivize use.

2.6 Emissions

Reductions in emissions is a large benefit to adopting BETs, though many figures only examine tailpipe emissions and neglect emissions from producing both fuel and electricity. Argonne National Laboratory's Greenhouse gases, Regulated Emissions, and Energy use in Technologies (GREET) model examines a broader emissions picture by incorporating national inventories and examining the full process for fuel and energy production [18]. Using outputs of the model in conjunction with data collected from the diesel tractors, energy estimates from the BET model, and emission information from the U.S. Energy Information Administration [19], Figure 30 provides a comparison of CO_2, NO_x, and sulfur oxides (SO_x) emissions between diesel and electric tractors. The plots on the left in Figure 30 show the emissions broken out by tailpipe and production. Tailpipe emissions are emissions generated by the truck, and production emissions are from producing fuel or electricity, depending on the technology. The BET (lower left plot) has zero tailpipe emissions compared to the diesel trucks (upper left plot), which is a large benefit to local air quality and reduces operator exposure to these emissions. However, when considering total emissions impact, emissions from fuel or energy production must be considered.

Combining these two emission types, the right plots highlighting the overall benefit from electric drayage truck adoption, with a 75% reduction in CO_2, 79% reduction in NO_x, and 75% reduction of SO_x for Fleet 1 trucks; 71% reduction in CO_2, 75% reduction in NO_x, and 71% reduction of SO_x for Fleet 2 trucks; and 69% reduction in CO_2, 75% reduction in NO_x, and 69% reduction of SO_x for Fleet 3 trucks. Extrapolated to all 58 trucks in Fleet 1, 93 trucks in Fleet 2, and 163 trucks in Fleet 3, adopting BETs would eliminate approximately 24,100 metric tons of CO_2 ($MTCO_2$) each year among all fleets, which equates to 76 $MTCO_2$ each year per truck with the existing energy production mixture, with further reductions as the electric grid switches to renewable energy.

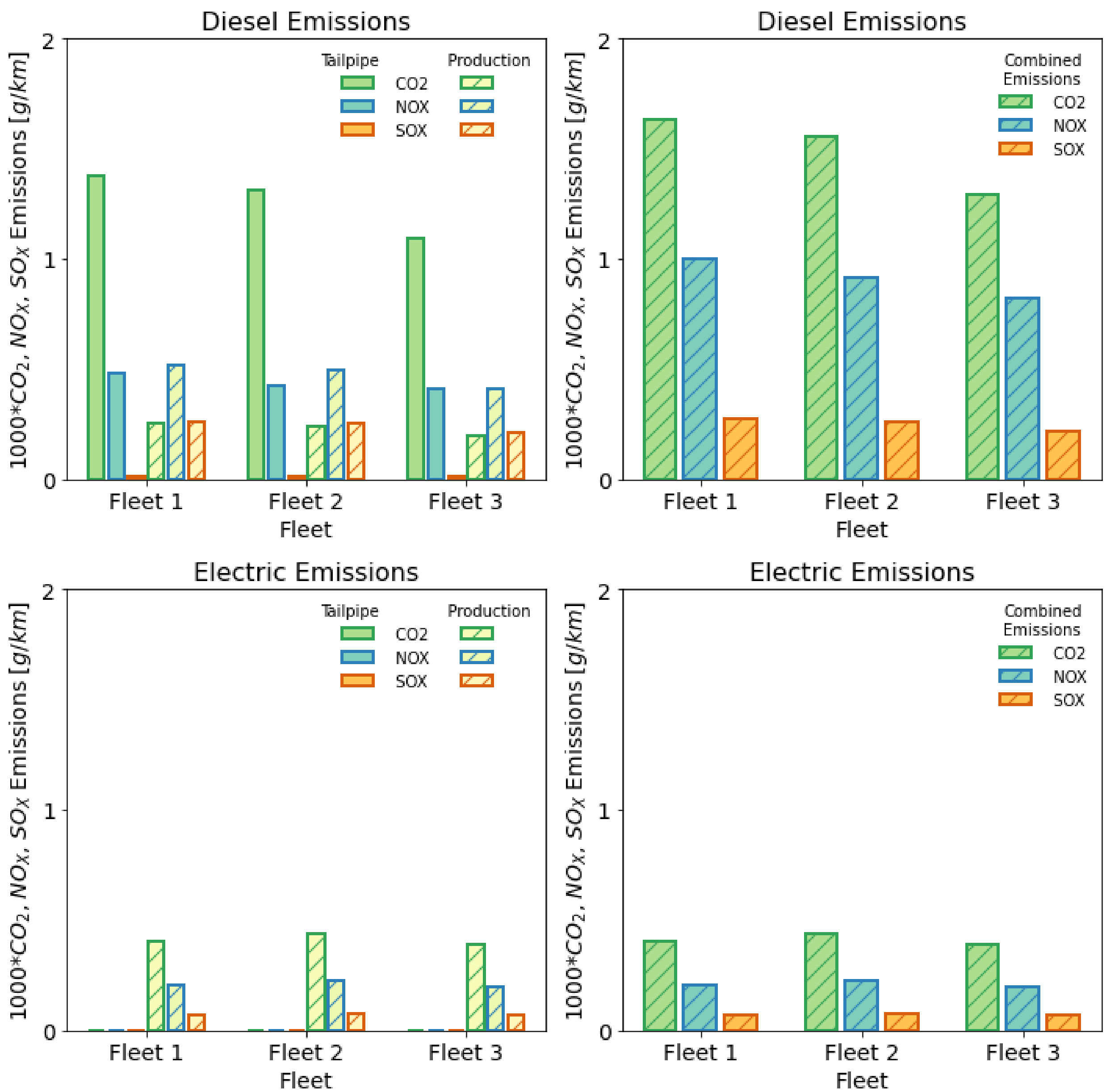

Figure 30. Emissions comparison between diesel and electric trucks for each fleet

2.7 Alternative Considerations

While electrification may not be immediately viable for all tractors due to technology limitations, other powertrains such as hydrogen fuel cell electric trucks may provide more near-term solutions for emissions reduction. Announced commercially available Class 8 hydrogen powertrains from Kenworth [20] and Nikola [21] are applicable to freight movement and are starting to become available [20], allowing for refueling times more comparable to diesel with lower emissions than existing diesel tractors. However, hydrogen fuel cell powertrains are typically less efficient than their BET counterparts, along with higher costs for hydrogen [3]. Further, hydrogen fueling infrastructure, like heavy-duty electric infrastructure, is extremely limited, and fleets would likely need to rely on fueling at their facilities.

Similarly, renewable diesel is another option for reducing carbon emissions and can reduce CO_2 by 73% [22] and could be a drop-in replacement for conventional diesel. However, like hydrogen, renewable diesel has limited options for fueling in the New York and New Jersey areas. Further, research has shown that NO_x emissions from trucks using renewable diesel can increase 26% to 77% over conventional diesel trucks [23]. Despite the available alternative powertrain options, this study focused on full battery-electric tractors.

3 Summary and Recommendations

NREL evaluated the potential for drayage electrification in the PoNYNJ with a focus on three operators: Harbor Freight Transport, Safeway Trucking, and International Motor Freight Inc. NREL subcontracted engineers from Energetics to install data loggers on 46 diesel drayage trucks at three different operators. Specifically, company-owned trucks were targeted for this study, and data were collected continuously over two separate 4-week periods from March to July 2021. This includes detailed operational data and identifies the performance requirements for BETs and corresponding infrastructure operated within the context of PoNYNJ drayage operation. This report also details a methodology to evaluate opportunities, strategies, and challenges associated with future expansions of BETs in meeting PANYNJ emissions goals of achieving net-zero carbon emissions by 2050 across all facilities, including from tenant and stakeholder sources such as drayage trucks [1].

Detailed performance data, including engine CAN and GPS position information, were monitored at 1 Hz, generating over 30 million data points and over 120,000 miles of data. The studied drayage trucks averaged 5.1 MPG, spent roughly 9% of their energy at idle, and drove an average of 140 miles per day with a maximum daily distance of 573 miles. Using the collected real-world performance data along with modeling and analysis tools, NREL compared the existing diesel truck operations to modeled BETs. A FASTSim electric truck powertrain model was validated using PoNYNJ data, and scenarios were run to evaluate drayage truck electrification requirements over the real-world cycles. The first scenario examined BET viability with minimal changes to existing operations. This assumes the trucks charge when stopped for 2 hours or longer, have a functional battery size of 375 kWh, and can charge at an average of 270 kW, which are the specifications of the commercially available Freightliner eCascadia. The second scenario looked at what operational, charging infrastructure, and BET technology changes would be needed to fully electrify. Finally, detailed analysis was run on charging rate structure to understand operational costs to the fleets.

FASTSim model results indicate a comparable BET would use 417 kWh per day on average accounting for cargo weight, which is close to the full usable capacity of the eCascadia. Further, some specific days of operation would require over 1,600 kWh of energy due to longer distances and more intense operation, which is not currently possibly without operational changes. However, partial fleet electrification is possible with current technology.

Models running under current operations scenarios, which means charging only occurs when trucks are stopped for 2 hours or more, indicate that with minimal change to operations 4 out of 12 trucks in Fleet 1, 4 out of 9 trucks in Fleet 2, and 1 out of 22 trucks in Fleet 3 could be electrified. This means they can complete all the measured daily routes using currently available BET technology and charging only during dwell periods (engine off) of 2 hours or longer at a rate of 270 kW with a usable battery capacity of 375 kWh. This model indicates that the existing Fleet 2 routes are the best near-term candidate for drayage electrification, followed by Fleet 1. The shorter routes operated by these fleets reduce overall energy requirements and provide more time for truck charging. Based on the data collected, it appears unlikely that all fleet operations could be fully electrified with current BETs without operational or technology changes. However, a portion of the routes could be electrified for all three fleets.

The second category of modeled scenarios explored requirements for full electrification, which can both serve as an outline for the PANYNJ in planning for future requirements and inform manufacturers when designing their next generation of BETs to meet real-world drayage requirements and send a signal to electricity providers regarding infrastructure needs and expected utilization. Full adoption of BETs could reduce CO_2 emissions from these fleets by roughly 75% today, eliminating 76 $MTCO_2$ per truck each year, which equates to 24,100 $MTCO_2$ per year for all three operators with current grid emissions, and further reductions as the grid emissions reduce. The specific scenarios that could lead to full electrification are as follows:

> *Scenario 1:* Results indicate that as larger battery options become available, Fleet 1 trucks could be fully electrified (all measured routes) with a 1,500-kWh battery and 175-kW charge rate; Fleet 2 trucks could be fully electrified with a 1,375-kWh battery and 100-kW charge rate; and Fleet 3 trucks could be fully electrified with a 1,600-kWh battery and 175-kW charge rate, all when charging for dwell periods of 2 hours or longer.

> *Scenario 2:* Increasing battery size, but also charging more frequently throughout the day to include 50-minute dwell periods, would allow Fleet 1 trucks to be fully electrified (all measured routes) with a 1,500-kWh battery and 175-kW charge rate; Fleet 2 trucks could be fully electrified with a 1,375-kWh battery and 100-kW charge rate; and Fleet 3 trucks could be fully electrified with a 1,000-kWh battery and 300-kW charge rate.

> *Scenario 3:* Operational, infrastructure, and technology changes that enable charging when they are stopped for 10 minutes or more would allow Fleet 1 trucks to be fully electrified (all measured routes) with a 1,500-kWh battery and 150-kW charge rate; Fleet 2 trucks could be fully electrified with a 1,250-kWh battery and 350-kW charge rate; Fleet 3 trucks could be fully electrified with a 900-kWh battery and 300-kW charge rate.

Based on the average daily modeled energy use for each operator and current industrial rate structures, full drayage electrification would increase electricity consumption by the values shown in Table 5, along with peak demand increases with unmanaged charging. It will be important for PANYNJ and the drayage operators within the PoNYNJ to consider these load impacts to their existing electrical infrastructure and devise operational strategies that avoid coincident charging of trucks to mitigate demand charges. Despite these electricity cost increases, savings from reductions in diesel consumption will help offset the costs of this increased electricity consumption. This shows BETs could be cost-competitive on an energy-cost-per-mile basis for all scenarios while diesel is above \$3.00/gal. Further, if diesel prices dropped to the 15-year low of \$2.33/gal, it would still be cost-competitive to operate the BETs with electricity costs of \$0.163/kWh or less.

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Appendix A.

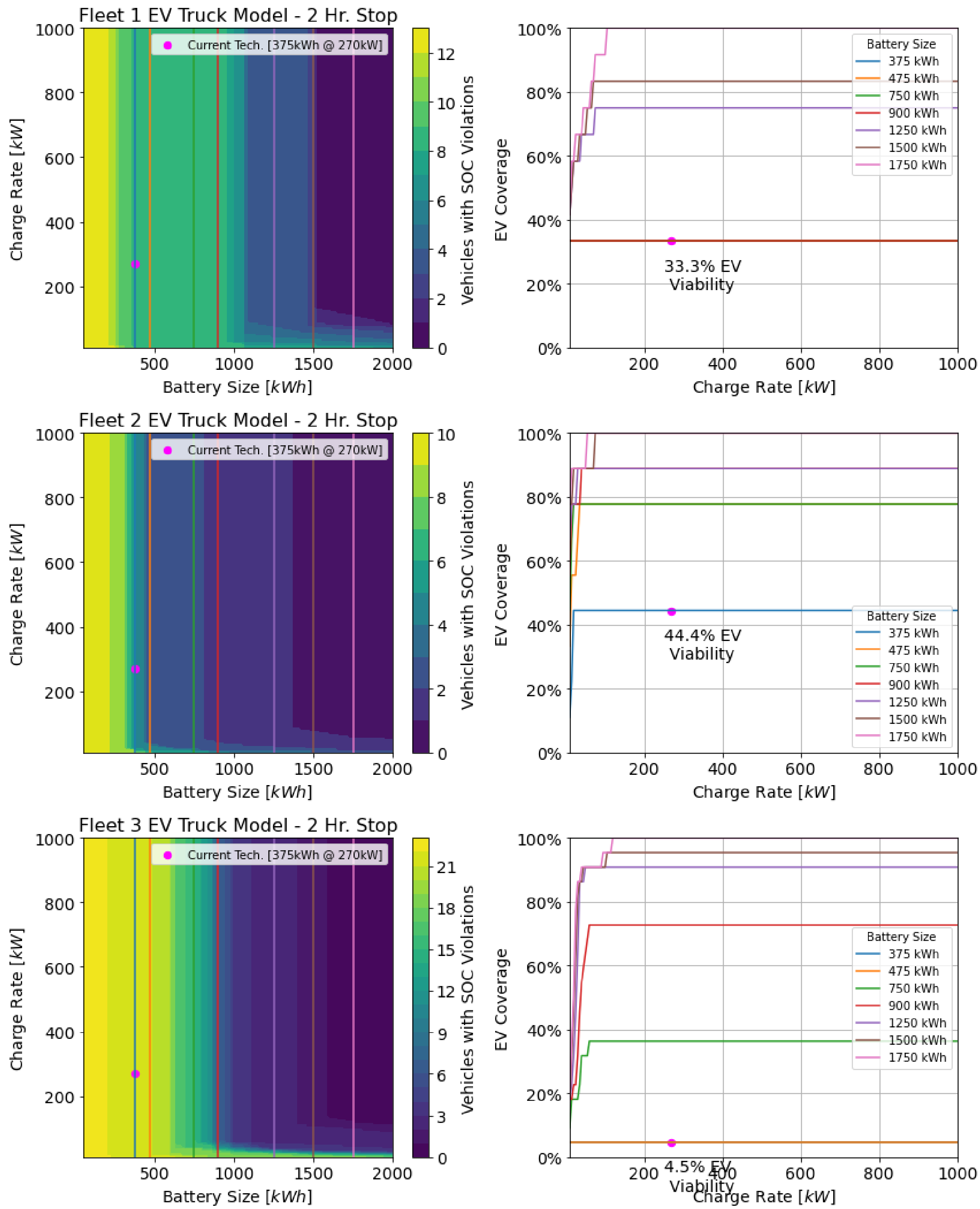

Figure A-1. Battery size and charge rate sweeps assuming charging during ≥2-h stop

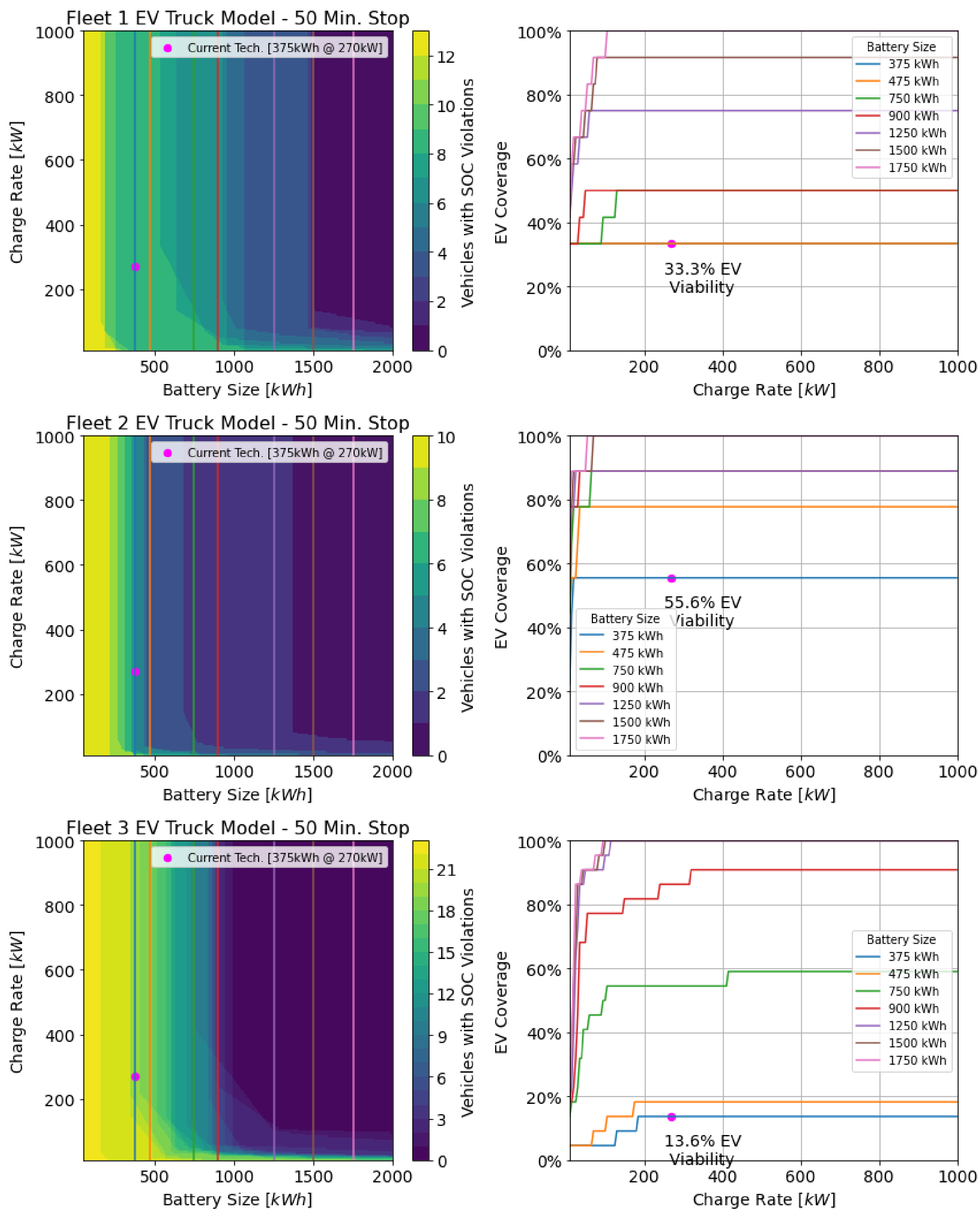

Figure A-2. Battery size and charge rate sweeps assuming charging during ≥50-min. stop

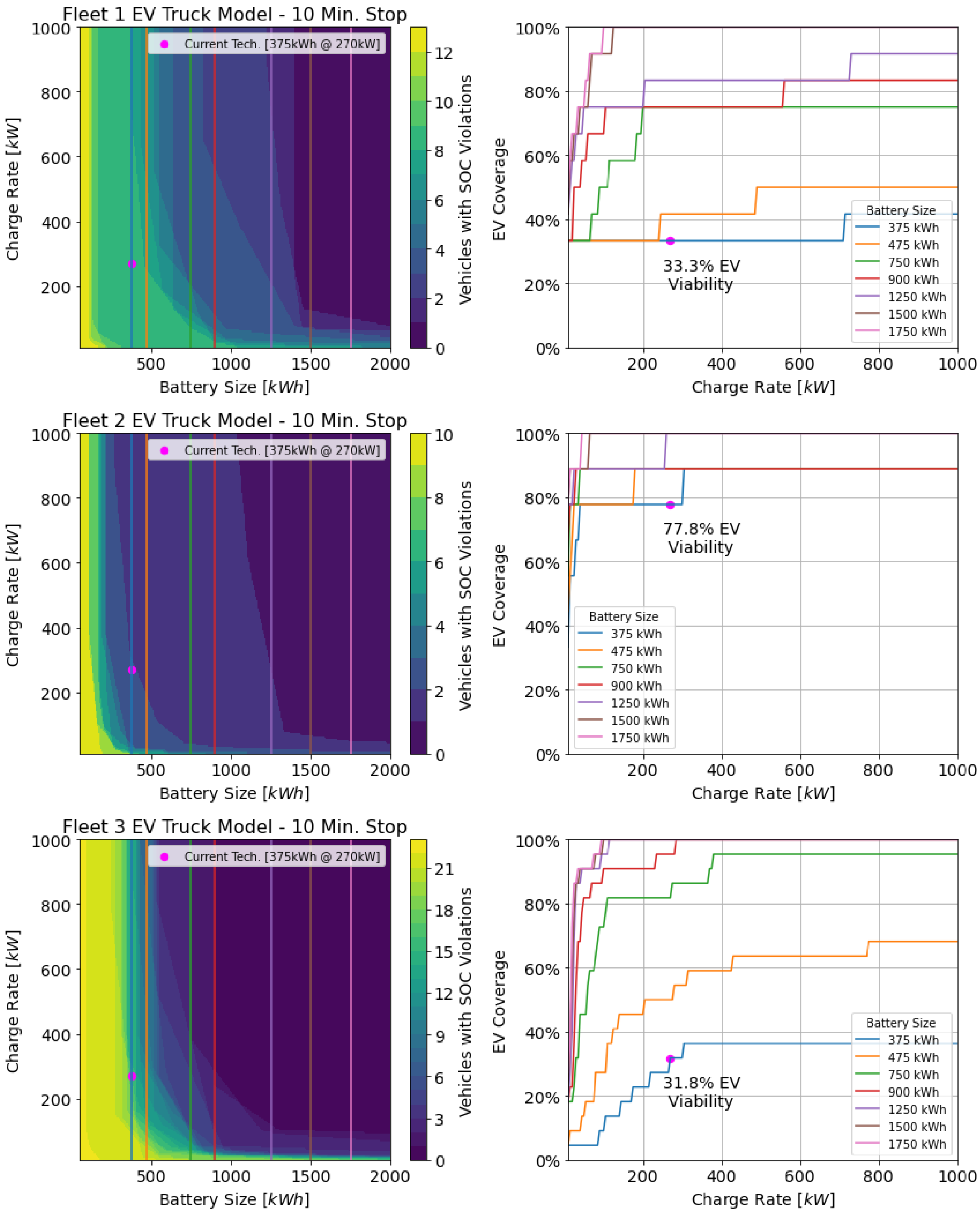

Figure A-3. Battery size and charge rate sweeps assuming charging during ≥10-min. stop