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System Impacts of an Electric Fleet Cluster on the Distribution Grid

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SUMMARY

In 2021, National Grid and Hitachi Energy published two papers at CIGRE's Grid of the Future Symposium, both evaluating the load implications for electric fleets.[1] Those papers showed the potential for significant electric load growth from fleet electrification and factors that would affect a fleet's charging profile. This paper reviews specific impacts on the electric distribution system from the load estimates seen in those papers, using the actual locations and grid equipment in the study area. It shows that large-scale fleet electrification can lead to loads that exceed the electric distribution system's capabilities and would require mitigation strategies, which are discussed in brief.

KEYWORDS

Electric Vehicles, EV, Fleets, Medium-Duty Vehicles, Heavy-Duty Vehicles, MHDV, Grid Impacts

[1] "Impacts of Fleet Electrification on Grid Infrastructure" and "Sensitivity Analysis of the Fleet Charging Impact on Feeder Load"

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Passenger EVs have seen considerable interest and growth recently, but fleet vehicles, including medium- and heavy- duty vehicles (MHDVs), are also poised to become more prevalent in the near future. A prior study by National Grid and Hitachi Energy and two prior CIGRE papers discuss the prospects for fleet electrification and, importantly, the implications of large load growth from this trend. [1] [2] [3] The prior documents outline three reasons that electric MHDVs are anticipated to be adopted, and there have been further developments in each space over the past year.

1. Policies Dictate that Electric Fleets Become More Prevalent

There have been significant advances in policy in National Grid's states of operation since the prior papers were published. In November 2021, New York passed legislation requiring 100% of medium- and heavy-duty vehicle (MHDV) sales be zero-emission by 2045.[2] In March 2022, as first filed in December 2021, Massachusetts adopted California's Advanced Clean Trucks (ACT) regulations, requiring sales of zero-emission MHDVs to begin in Massachusetts in model year 2025 (which begins in 2024).[3]

2. Fleet Activity is Well-Suited for Electrification

A report by RMI, *Charting the Course for Early Truck Electrification*, says, "based on how vehicles are driven today, approximately 65% of medium-duty trucks (MDTs) and 49% of heavy-duty trucks (HDTs) stationed in California and New York are electrifiable, meaning they could be replaced with EVs based on current technology. These vehicles are responsible for about 30% of the vehicle miles traveled by trucks based in the two states."[4] While there are segments that could not be electrified today, future developments in batteries, vehicles, and public charging infrastructure could open additional use cases to electrification over time.

3. Total Cost of Ownership Will Increasingly Favor Electric Fleets

A study from Roush and the Environmental Defense Fund, released in February 2022, finds that, by 2027, every type of vehicle studied will have a lower total cost of ownership (TCO) for an electric model than diesel engine counterparts.[5] By then, too, most electric models are expected to have lower purchase prices as a result of battery cost declines and efficiencies in manufacturing lines.

Those results do not include charging infrastructure or needed grid infrastructure, both of which would add costs to EVs. Minimizing the costs of new and upgraded grid infrastructure, as discussed in later parts of this paper, will be important to ensuring that TCOs do favor EVs and that fleets therefore do convert to electric models.

[2] https://www.nysenate.gov/legislation/bills/2021/A4302
[3] https://www.mass.gov/news/massdep-files-new-regulations-to-reduce-emissions-advance-market-for-clean-trucks-in-the-commonwealth
[4] Jessie Lund, John Schroeder, Emily Porter, and Dave Mullaney, Charting the Course for Early Truck Electrification, RMI, 2022, https://rmi.org/insight/electrify-trucking/
[5] https://www.edf.org/media/new-study-finds-rapidly-declining-costs-zero-emitting-freight-trucks-and-buses

Growth of EV Penetration

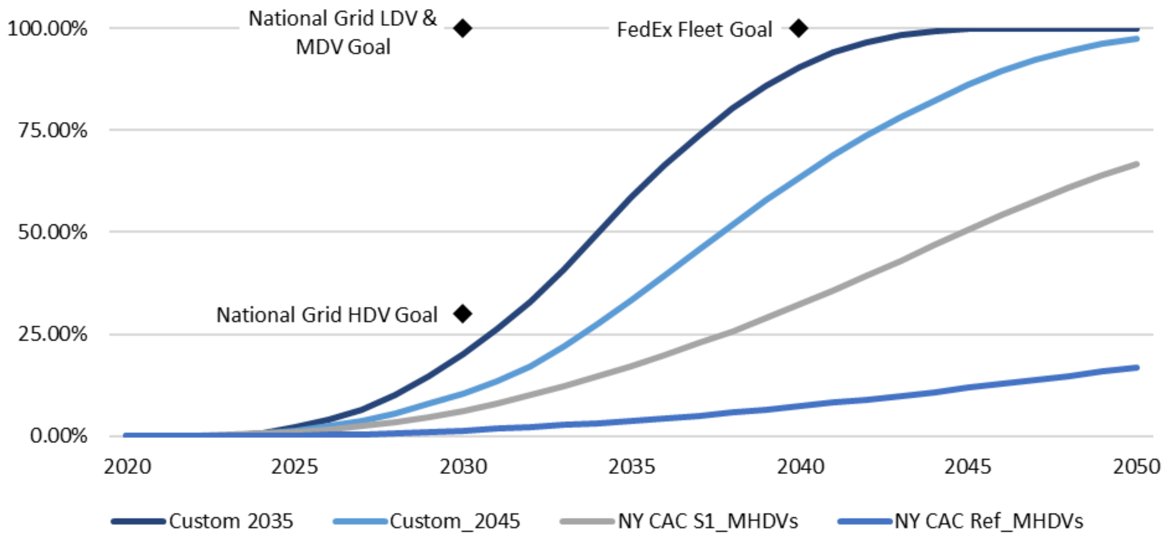


Figure 1: Forecasted Growth of Medium and Heavy-Duty Electric Vehicles, Percentage of Population[6]

The timing of electric grid impacts will be dictated by the pace of electric vehicle adoption. Three categories of scenarios for MHDV adoption of EVs are considered below:

Category	Reference Scenarios	Description and Implications
Conservative Adoption Scenarios	Reference Case Scenario (New York State Climate Action Council)	Business-as usual, no added policy support. **Not consistent with Net Zero goals or accelerated market adoption.**
Policy-Driven Adoption Scenarios	Advisory Panel Recommendations Scenario (S1) (New York State Climate Action Council)	Reflective of Net Zero ambitions and state goals; differ in share of EV vs other technology. Consistent with CA ACT. **Useful in planning for EV adoption across a state / region.**
	100% Electric MHDV Sales by 2045 (National Grid Custom Scenario for Internal Analysis)	
Accelerated Adoption Scenarios	100% Electric MHDV Sales by 2035 (National Grid Custom Scenario for Internal Analysis)	Reflective of accelerated adoption curve for electric MHDVs. **Useful in planning for strategic electrification of a fleet "cluster" in a specific location / accounting for more aggressive electrification mandates of specific fleets.**

When planning for load impacts, it may be useful to plan for "accelerated scenarios," as it may be preferable to target grid investments to fully electrify fleets in certain geographic areas – for instance, an industrial area where many fleets are concentrated. An accelerated

[6] Note that these lines are only the percentage of EVs of vehicle stock. The 133% scenario presented in the analysis below is used to reflect potential higher loads than estimated, including from increases in vehicle stock.

scenario may also better reflect the timelines for large fleet operators; for instance, FedEx has a corporate commitment to electrification that includes up to 100% electric purchases by 2030, even faster than the accelerated scenario shown, with goals for all vehicles in operation to be electric by 2040. National Grid has recently committed to electrifying 100% of medium-duty vehicles and 30% of heavy-duty vehicles by 2030. This case study of one such geographic area provides an understanding of the load impacts which may be seen at varying adoption levels, even faster than policy dictates.

Distribution Grid Impact Preliminaries

Typically, the impacts of the increasing load on the distribution grid or the connection of the large loads on the grids can be quantified in terms of the line loading and the power quality issues. EV chargers typically operate at unity power factor. Hence, the power factor at the point of interconnection is maintained within limits. This section provides an overview of the frequently observed impacts of high charging loads.

Thermal overload

Thermal overload occurs when the nominal ampacities of the distribution grid cable/conductors or devices are reached. Typically, the device manufacturer specifies the device ratings which are often revisited by the local utilities. The conductor ratings are defined for nominal operating conditions as per NESC, ANSI and IEEE standards. In addition, devices and conductors also have an emergency ampacity rating to withstand temporary or short-term overloads. EV charging load typically has a higher duty cycle (due to continuous charging at the rated capacities of the EV charger). Hence, nominal thermal ratings are recommended to study for EV charging station interconnections and to identify the potential system overloads and associated system upgrades required for interconnection.

Undervoltage

Regulators or tap-changing transformers and capacitors primarily provide voltage regulation at the distribution level. As per the ANSI C84.1 standard, the voltage throughout the distribution grid should remain within the range of 0.95 to 1.05 pu [7]. If voltage regulating infrastructure is inadequate or malfunctioning, the violation of voltage operating limits may occur. An undervoltage is an RMS increase in AC voltage lesser than 0.95 pu for a duration longer than 1 min. Undervoltage conditions typically occur in a distribution grid with high demand and absence of voltage regulating devices. The lower voltage levels further increase the feeder head's current and thereby the grid's losses. The magnitude of the increase in the current depends on the types of loads on the feeder. Loads at the feeder end are more susceptible to the under-voltage scenarios because of higher voltage drop.

Active Power Loss

Typically, fleets prefer charging in the local parking area where the dwell times are utilized efficiently for charging and regular loading/unloading operations of each vehicle. The losses on the distribution grid vary based on the fleets' location, upstream conductors, and the length of the feeder. For example, a fleet located at the end of the feeder with 2MW charging demand will see higher losses compared to a fleet located near the feeder head. Relocating a fleet to reduce the distribution grid losses may not be an economically viable option for the fleet owner.

Study Approach

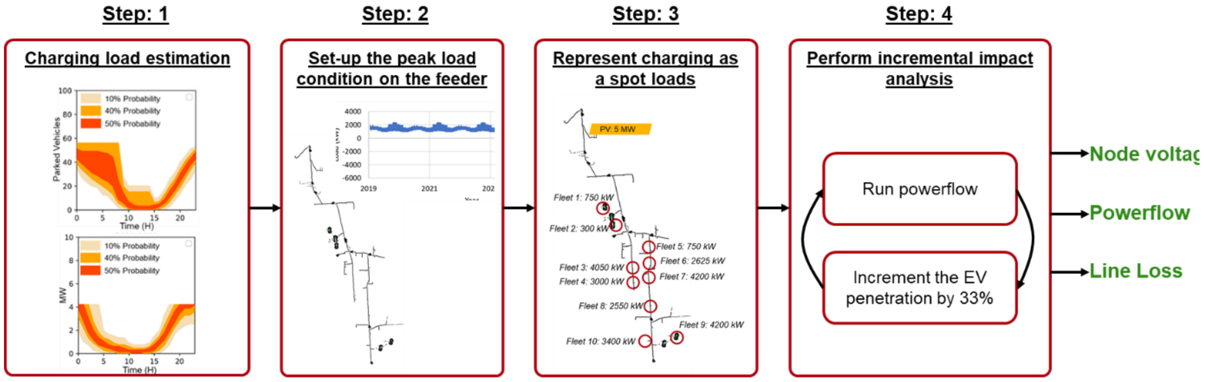


Figure 2: Incremental impact analysis of the fleet electrification

Figure 2 shows the four-step approach adopted to analyze the grid impact due to increasing fleet electrification.

Step 1: Charging Load Estimation

A Monte Carlo-based framework estimates the charging load for each fleet within the study area [1]. Charging load calculations considers the following factors for each fleet: size of the fleet, service provided by the fleet vehicles, compatible chargers, driving efficiency, dwell time, charging strategy and operating temperature. Complete architecture for the charging profile calculation is explained in detail in [1][2] and [3]. An aggregated charging profile generated for the on-arrival full charging strategy is used to determine the peak charging load for each fleet.

Step 2: Feeder model configuration

The CYME model for the impacted feeder is configured for the worst-case scenario. The measured annual peak load is considered a worst-case. DER generation located on the feeder, being intermittent, is not considered for the analysis. The feeder-head voltage is set to 1.025 pu.

Step 3: Charging load representation

Then the spot loads representing the EV charging loads are connected at each pre-existing commercial fleet load. In addition, all residential loads are assigned a load multiplication factor to represent the EV penetration at the residential level.

Step 4: Perform incremental impact analysis

Incremental analysis is performed by gradually increasing the magnitude of the spot loads representing the fleet charging. The increments are made as a percentage of the expected peak load. Also, the load multiplication factor for the residential load is increased to represent the electrification of LDVs. It is assumed that the penetration of electric vehicles among the fleets would be uniform for all fleets within the study area.

Case Study: National Grid Feeder

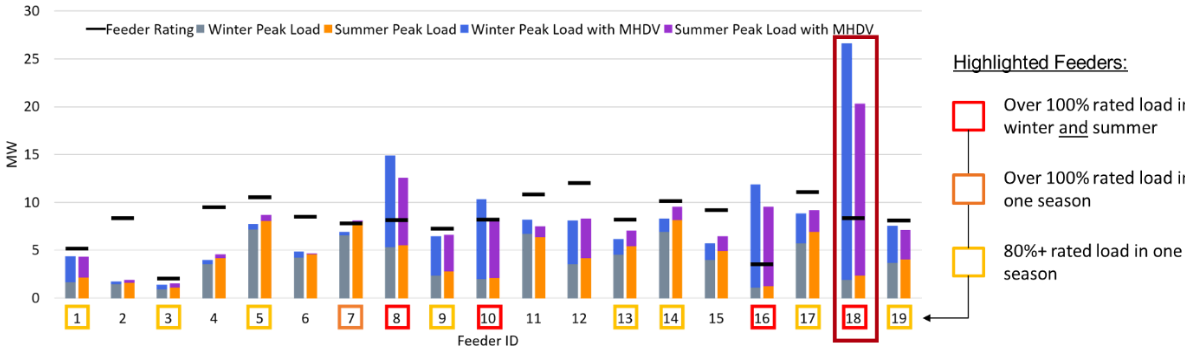


Figure 3: Impact of fleet charging load on the feeder loading

National Grid and Hitachi Energy identified 19 feeders that may see fleet interconnectivity clusters. For all feeders, the fleet charging load is calculated using the Monte Carlo approach considering the size, class of vehicles and service provided by the fleets (Step 1), as discussed in the previous section. The impacts to the feeder loading were determined by stacking the charging load for all fleets supported by a feeder over the maximum load observed by the feeder. Figure 3 summarizes the study results for 19 feeders supporting 51 fleets within the study area. Of the 19 feeders, Feeder 18 is expected to see the highest impact from fleet electrification. This paper presents a detailed study to quantify the impacts of fleet electrification in terms of thermal and voltage violations.

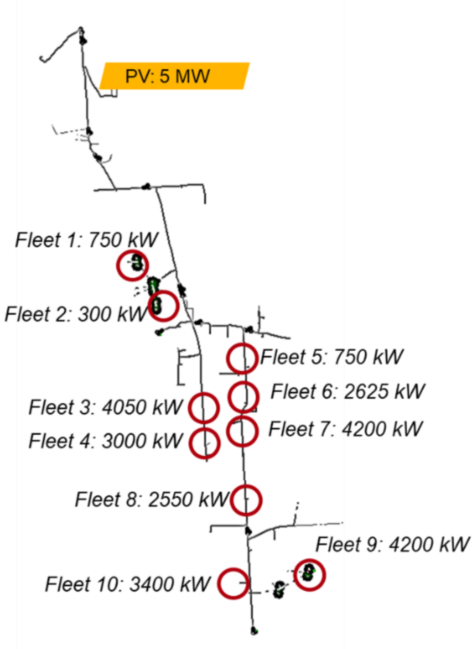


Figure 4: Feeder 18 topology

Current State of the Feeder

Feeder 18, along with the fleet locations, is shown in Figure 4. This is a 13.2kV feeder with a rated capacity of 8.2 MVA during summer and 9.85 MVA during winter. The current peak loading of 2 MVA is measured during the summer. 88% of the total load on the feeder is industrial, and 12% of the load is residential. Hence, the expected residential charging load on the feeder is minimal.

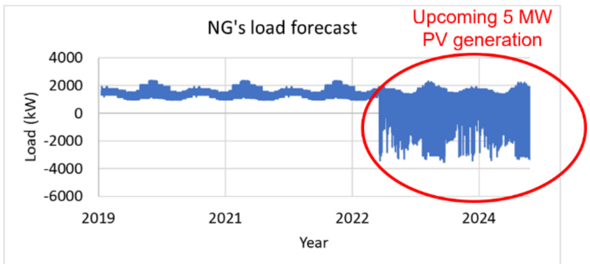


Figure 5: Feeder net-load profile with forecast

Table 1: Feeder sections		
Type	Total Length (ft)	Ampacity (A)
3P_1/0_AAAC	263	256
3P_1/0_ACSR	7,854	242

3P_336.4_ACSR	5,011	519
3P_336.4_SAL	28,369	514
3P_4/0_SCU	1,747	333
1000_CU	108	480
2_AL	42,35	137
2_SAL	3,223	183
750_AL	2,974	477

The feeder is supported by a 115/13.2kV substation transformer rated at 37.4MVA. The busbar supports additional 2 feeders with the peak load of 6.6 MW and 7.3 MW. The voltage on the feeder is regulated at the feeder-head by the transformer LTC. The feeder currently has no additional voltage regulating devices such as capacitors and voltage regulators. Table 1 summarizes the types of cables and conductors on the feeder.

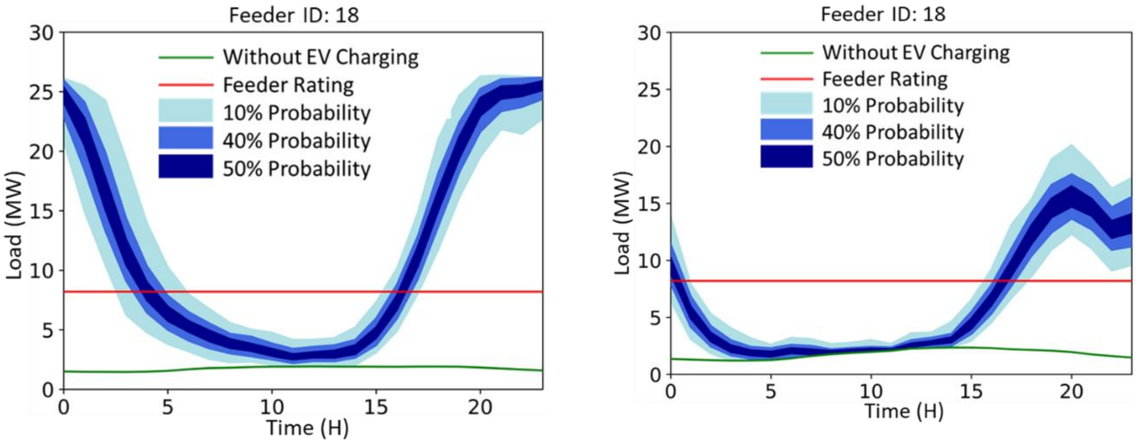
The 5MW PV facility near the feeder's head (as shown in the Figure 4) is expected to interconnect by the end of 2022. The PV generation will be supported by 5MW, 20 MWh battery. Figure 5 shows the forecasted net-load profile with PV generation coming online by mid-2022. Since the feeder is lightly loaded, the peak PV generation would result in the reverse power flow (~3.8 MVA). Considering the intermittent nature of the distributed generation on the feeder, and that the fleet loads are forecast to peak overnight, it is assumed that the forecasted load peak remains the same and the solar DG does not improve the loading capacity of the feeder.

Fleet Charging Load Forecast

Table 2: Fleets supported by the study feeder

Fleet ID	Number of vehicles	Type of vehicle	Number of Chargers	Charger Rating	Total Charging Load (kW)
1	10	Distributor Regional freight trucks (drayage)	5	150	750
2	12	Box Truck	6	50	300
3	54	Distributor Regional freight trucks (drayage)	27	150	4,050
4	40	Distributor Regional freight trucks (drayage)	20	150	3,000
5	10	Distributor Regional freight trucks (drayage)	5	150	750
6	35	Distributor Regional freight trucks (drayage)	18	150	2,625
7	56	Distributor Regional freight trucks (drayage)	28	150	4,200
8	34	Distributor Regional freight trucks (drayage)	17	150	2,550
9	56	Distributor Regional freight trucks (drayage)	28	150	4,200
10	136	Box Truck	68	50	3,400

The fleet charging load for 100% fleet electrification is based on the fleet size, types of fleet vehicles, and services offered by the fleets. Table 2 provides information on the type of fleet vehicles and the estimated size of the fleets located within the service area of the feeder. The charging infrastructure (charger rating and count) are “right-sized” to meet the fleet charging requirement in case of 100% fleet electrification [2][8]. As discussed in [2] and [9], the battery efficiency varies based on the operating temperature. Hence, the charging requirements are higher during the winter (~35%) compared to summer [2]. Figure 6 shows the estimated feeder load during summer and winter, including the fleet charging. Since the feeder is rated at 8.2 MVA, the fleet charging will overload the feeder by 248% during summer and 325% during winter.



(a) Winter (b) Summer

Figure 6: Feeder loading due to fleet charging load

The growth in the light, medium, and heavy-duty EV's, along with the contributing factors, is described in Section 1. The growth in EV charging load in the study area is then calculated by scaling the EV growth based on the expected charging load peak at 100% electrification of vehicles. Figure 7 shows the growth in residential, public, and fleet charging load within the study area. The charging growth curve is essential in optimizing the distribution planning approach to meet the increasing charging loads. The current work will quantify the charging load impact for the 33%, 67%, 100%, and 133% EV penetration. The 133% EV penetration scenario is aimed to address the growing local economy, the additions of the new fleet of vehicles and customers within the study area, and possible higher charging demand than estimated in the analysis.

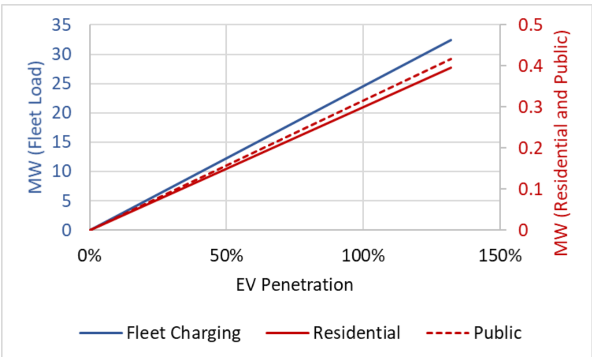


Figure 7: Growth in EV charging load on the feeder

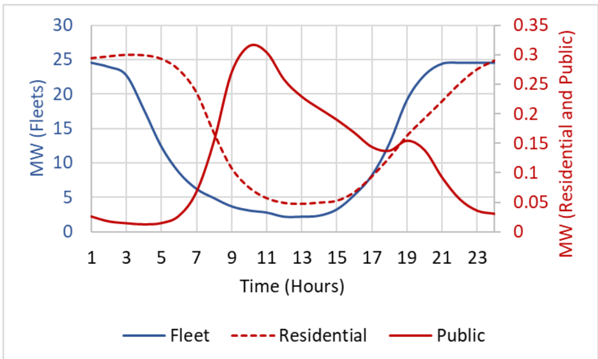


Figure 8: Forecasted peak charging load for 100% electrification scenario.

Distribution System Impacts

Table 3 shows the charging load for EV penetration to be 33%, 67%, 100%, and 133% for Feeder 18 and its respective substation. Since the substation transformer also supports additional two feeders, the charging load experienced by three feeders is aggregated at the substation. This section analyzes the charging load's thermal loading and voltage impacts at the substation devices and feeder 18.

Table 3: Feeder and substation loading

	Substation Transformer				Feeder 18			
% EV Penetration	Base Load (MW)	Fleet Charging (MW)	Residential and Public (MW)	Total (MW)	Base Load (MW)	Fleet Charging (MW)	Residential and Public (MW)	Total (MW)
0%	16	0	0	0	2.1	0	0	0
33%	16	9.4	1.1	10.5	2.1	8.5	0.5	9.1
67%	16	18.8	2.2	21.0	2.1	17.0	1.1	18.1
100%	16	28.5	3.4	31.9	2.1	25.8	1.6	27.5
133%	16	37.6	4.5	42.1	2.1	34.0	2.2	36.2

Feeder Overloading

Figures 9 and 10 show the feeder sections' overload with increasing EV penetration. Currently, the feeder is lightly loaded with 2MW of the commercial and industrial loads and does not experience any thermal violations. However, at 33% EV penetration, 88 sections are violated with a total length of 2.4 miles. The length of the overloaded section increases to 3.5 miles at 67% penetration. At 100% EV penetration, all upstream sections (total length of 4.72 miles) violate the thermal limits by >330%.

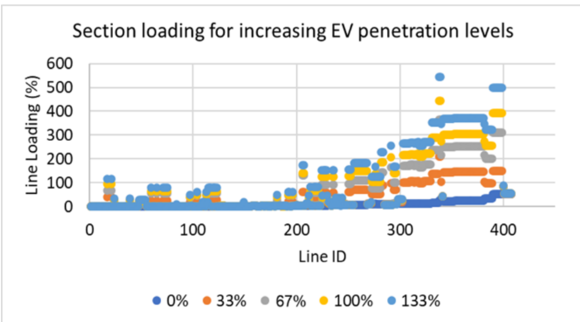


Figure 9: Thermal loading of the feeder sections

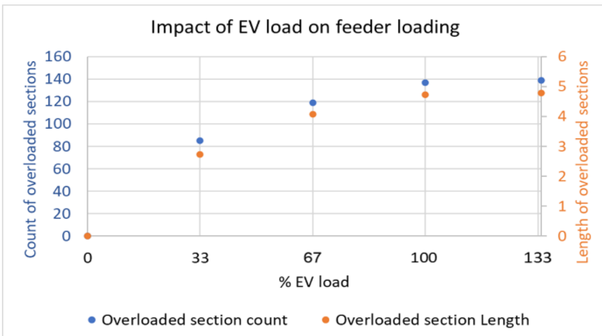


Figure 10: Length of overloaded sections

Table 4: Feeder overload for increasing EV penetration level

Penetration level	**Affected length (miles)**	**Overload %**
33%	2.42	Up to 209%
67%	3.82	Up to 364%
100%	4.72	Up to 444%
133%	4.72	Up to 544%

Feeder Voltage Issues

Feeder 18 has no voltage regulating device downstream. Since the substation transformer supports the additional feeders, the feederhead voltage of 1.025 pu is the recommended level. Figure 11 shows the voltage level at all feeder nodes for different EV penetration levels. For the base load condition, the voltage levels for all nodes are within the operable limits. The voltage violations are observed at selected nodes for 33% level EV penetration, where the selected nodes go to around 0.93pu; this may be regulated by the addition of a voltage regulation device. However, the voltage dips below 0.9 pu for >67% EV penetration on >80% of the feeder nodes may not be improved through the addition of a voltage regulating device. The lower voltages on the distribution system will result into higher losses on the grid.

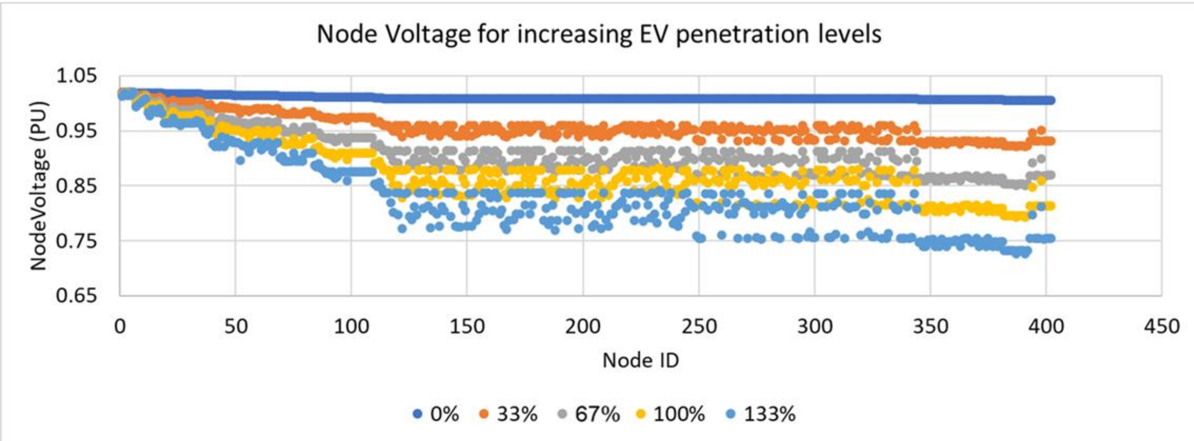


Figure 11: Effect of increasing fleet charging on the feeder voltage profile.

Table 5: Impact of increasing EV penetration level on feeder node voltages		
Penetration level	**Affected Nodes**	**Undervoltage %**
33%	149	0.92
67%	328	0.85
100%	352	0.79
133%	365	0.73

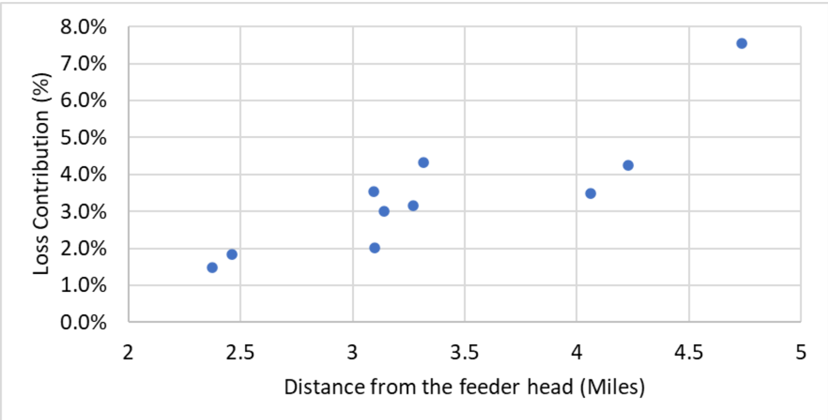


Figure 12: Sensitivity of the system loss to the fleet locations

Active Power Loss

As discussed above, the existing location of the fleets is agnostic of the grid impacts at 100% electrification of vehicles. Hence, the fleet charging near the feeder end may contribute to higher loss than those near the feeder-head. Figure 12 shows the variation in the contribution to the system loss for each fleet. The fleets near feeder-head (<2.5 miles from the substation) contribute up to the 2% of the rated charging load towards the feeder loss, whereas the fleets located near the feeder-end would contribute up to 8% of the rated charging load towards the system active power loss. The losses further increase with the increasing penetration of electric vehicles on the feeder due to a lack of voltage regulation and feeder section resistivity. Table 6 shows the increase in the loss with the increase in the charging load.

Table 6: Variation in System Losses with Increasing EV Penetration

Penetration Level	Loss (kW)
0%	19
33%	555
67%	2,169
100%	2,697
133%	4,150

Substation Overloading

The substation layout, along with the ratings, is represented in Figure 13. The thermal loading on the substation devices is represented in Figure 14 and Table 7. Most of the substation devices may warn for the thermal overload for EV penetration>33%. Substation transformer experiences the loading >100% for EV penetration of 67%. At 100% EV penetration, all substation devices are expected to violate the thermal ratings, thereby indicating a requirement to plan for the upgrade to address the increasing EV penetration.

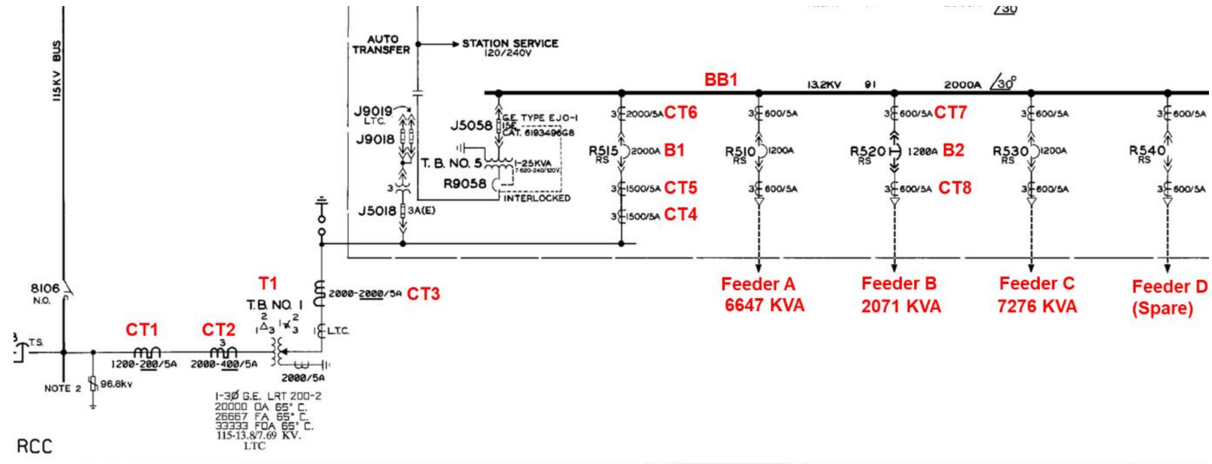


Figure 13: A simplified substation layout showing the devices carrying the load of the feeder

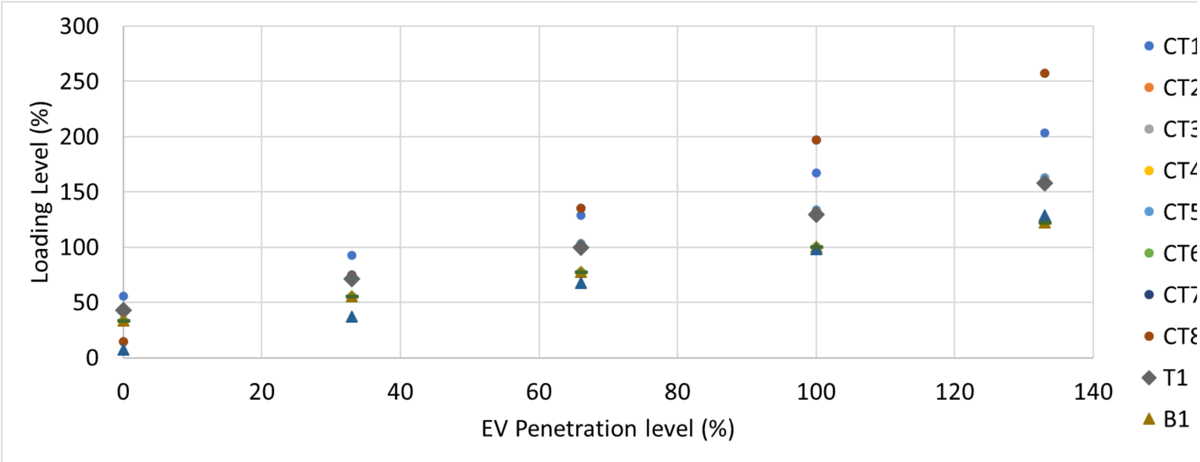


Figure 14: Showing the loading level of the devices at different levels of the EV penetration

Table 7: Impact of fleet charging load on the substation device loading						
Device	**Device Ratings**	**Overload (%)**				
Penetration Level è		**0%**	**33%**	**67%**	**100%**	**133%**
CT1	1,200 A	55.8	92.5	129.2	167.0	203.7
CT2	2,000 A	33.5	55.5	77.5	100.2	122.2
CT3	2,000 A	33.5	55.5	77.5	100.2	122.2
CT4	1,500 A	44.6	74.0	103.4	133.6	163.0
CT5	1,500 A	44.6	74.0	103.4	133.6	163.0
CT6	2,000 A	33.5	55.5	77.5	100.2	122.2
CT7	600 A	14.4	74.8	135.1	197.3	257.6
CT8	600 A	14.4	74.8	135.1	197.3	257.6
T1	37,000 kVA	43.2	71.7	100.2	129.5	157.9
B1	2,000 A	33.5	55.5	77.5	100.2	122.2
B2	1,200 A	7.2	37.4	67.6	98.7	128.8
BB1	2,000 A	33.5	55.5	77.5	100.2	122.2

Transmission Level Impacts

In addition to the impacts of EV adoption on specific areas of the distribution system, it is important to be aware of the impacts that will be seen by the broader system. The transmission impacts of EV adoption covering the entire study area were studied under various scenarios to identify N-1 and N-1-1 violations. The solutions required for the N-1 violations included the replacement of a current transformer, reconductoring of roughly half a mile of an overhead transmission line and its station connections, and operational changes to prevent further upgrades. The solutions required for the N-1-1 violations included reconductoring of multiple miles of both overhead and underground transmission lines, reconductoring of specific station connections, and multiple operational changes to prevent further upgrades. There will be impacts seen on all levels of the electricity system, and it will be vital to stay ahead of any issues that may arise. Studying future changes on the electricity system allows adequate planning to mitigate impacts felt by all customers.

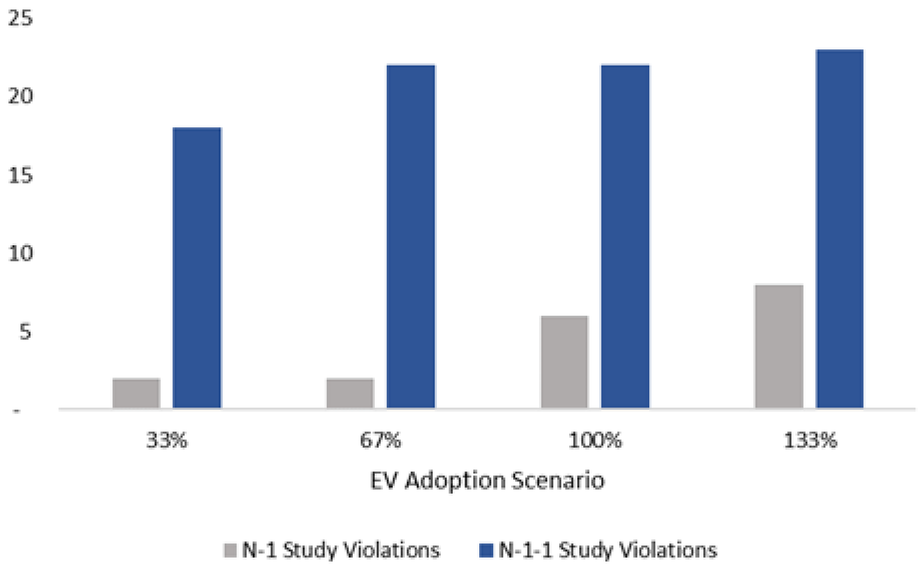


Figure 15: Number of Transmission System Violations Observed in N-1 and N-1-1 Studies with Case Study Area's EV Loads

System Mitigation Options

The study quantifies the impact of the increasing EV penetration on a National Grid feeder. The feeder currently supports a cluster of major fleet operators. Hence, electrification of the medium and heavy-duty vehicles is expected to significantly impact the feeder. The study also forecasts the impact associated with the increasing penetration in medium- and heavy-duty vehicles and provides guidance to distribution system planners to prepare for the infrastructure projects to address the increasing electrification requirements over the coming years. Various strategies may be implemented considering the growth rate of electrification and the cost and lead times for the implementation of the strategies.
Table 8 provides an overview of the possible mitigation strategies to address the distribution system impacts. Each mitigation strategy has its pros and cons which limit the application of an individual strategy to address overload issues due to fleet electrification. Hence, a coordinated planning approach that may leverage a mix of mitigation solutions may be required to address the distribution system impacts and prepare for the future load demand attributable to charging of electrified fleets.

Table 8: Mitigation options to address increasing EV charging loads on the feeder

Strategy	Benefits	Limitations
Load Transfer	Easy to implement. Lower Lead times if feeder ties are available Lower cost of implementation	May require installation of additional switches at selected locations. Protection coordination studies will be required. Effectiveness limited to the capacity available at the adjacent feeders

		Reduces adjacent feeders capacity to serve new native load (EV, electrification of heating...). Frequent feeder switching for normal system conditions (i.e. no contingency) is not typically used as a planning solution Impacts the system resiliency by limiting reconfigurations during the feeder outages
Feeder and Substation Upgrades	Effective solution and easier to implement than a new substation, but may not meet long-term, full electrification scenario and impacts on distribution voltage levels and available conductor capacities Improvements in system resilience, but not as much as a new substation. Voltage regulation may be an effective solution to address feeder voltage issues	High lead times depending on the scope of upgrade High cost of implementation depending on scope of upgrade.
New Substation (Transmission to Distribution)	Long term solutions effective in addressing the high EV penetration level, leveraging available capacity on the transmission network Improves system resiliency and can provide other benefits such as increased hosting capacity for both generation and additional demand.	High lead times High cost of implementation
Non-Wires Alternatives	Under specific circumstances, can be a cost effective and/or more rapid solution to address the localized impacts compared to network infrastructure upgrades Could improve system resilience with the possibility of an	Can vary from low to high lead times Can vary from low to high cost of implementation. The net-cost of implementation may be lower if fleet operator and user behavior can be managed such as charging during more optimal times or incorporating co-located energy

	islanded operation and support to critical loads Possible additional benefits can be realized if able to participate in markets such as providing ancillary services	storage. Additional revenue from market participation, reduction in demand charges or demand response programs may also impact overall net benefits of a non-wire alternative. DER could overload the feeder at light load with too much generation. Energy storage requires management at peak to not overload the distribution feeder while charging

Conclusions

Due to the tendency of fleets to "cluster" in industrial areas, load impacts from fleet electrification will be felt acutely at certain areas of the grid. Even early stages of fleet electrification could introduce substantial amounts of new electric demand to these areas: at 33% adoption of electric vehicles, peak electric demand in the case study area would more than quadruple. At that point, almost half the 5-mile distribution circuit would be overloaded, with some sections reaching 150% of their rating. At higher levels of penetration, the substation components will face overload, as well.

This will require a mitigation strategy. In determining approach, it will be valuable to consider: the time required to implement a given solution; the pace of electrification; cost; and the likelihood of requiring additional upgrades in the future. Solution design should also consider that many fleets have more aggressive electrification timelines than policy or market forecasts suggest, and that these fleets may be especially likely to "cluster" in industrial areas like the one studied. In these instances, designing solutions that account for future demand may be cost-effective and actually accelerate timelines for electrification by providing needed grid capacity.

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