38th International Electric Vehicle Symposium and Exhibition (EVS38)
Göteborg, Sweden, June 15-18, 2025

Power Flow Calculation for Analyzing the Effect of Electrifying Light-Duty Trucks on Distribution Line

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Executive Summary

In Japan, commercial vehicles emit 40% of the CO_2 from the transport sector, making their electrification essential for reducing emissions. To address this, the Japanese government launched the Smart Mobility Society Construction project in FY2022. Electrifying these vehicles will increase energy demand for charging, which poses challenges to the power grid, particularly causing voltage drops in local grids. We focused on light-duty trucks for distribution delivery and analyzed the impact of electrifying commercial vehicles on voltage variation through power flow calculations. We found that optimizing charging schedules to minimize electricity costs at depots can help suppress energy demand and prevent voltage drops, Whereas the simultaneous charging of trucks after business hours may cause severe voltage drops.

Keywords: *Electric Vehicles, Modelling & Simulation, Energy management, Consumer demand, Smart grid integration and grid management*

1 Introduction

In Japan, the electrification of mobility is proceeding as well as in other countries. Actually the total number of battery electric vehicles and plug-in hybrid electric vehicles in new sales in 2025 has increased three times from 2022 [1].
In particular, the electrification of commercial vehicles is focused on now. In Japan, commercial vehicles are emitting 40% of the CO_2 from the transport sector. This value is not negligible for reducing CO_2 by electrifying mobility. Therefore, the Japanese government launched a project called Smart Mobility Society Construction in FY2022 to accelerate the electrification of commercial vehicles [2].
In this project, the effect of electrifying commercial vehicles has been studied from several viewpoints such as the economic profit for the owners of vehicles and the power grid. Their installation of many charging infrastructures is essential for the electrification of commercial vehicles, but the installation and utilization will change the economic profit for the owners and the power flow in the power grid.
We focused on the effects of electrification on local power grids such as distribution systems and discuss them in this report. It has already been reported that the electrification of mobility will increase the power flow in distribution systems and make the voltage control by the distribution system operator (DSO) more difficult [3]. There are many examples of studies of such problems but most of them target passenger vehicles.
As a first step to evaluate effect of electrifying commercial vehicles on local power grid, we choose light-duty trucks for distribution delivery as the target. This was because the driving schedules of such trucks

are almost the same, and it is easier to predict the timing of charging EVs than other types of commercial vehicle.
In the simplest case, the trucks are expected to charge at their depots after completing their delivery, and the power flow on the distribution line will increase at night. On the other hand, some depots are also expected to suppress the net demand by using energy management systems (EMS), and the related research on this issue has already been proceeded.
In this study, the authors aimed to evaluate the effect of electrifying light-duty trucks for distribution delivery on voltage variation in a distribution system. For this purpose, energy consumption at depots is estimated for two cases: charging the trucks after the operation time and scheduling the charging timing with EMS. The power flow and voltage in the distribution system were calculated on the basis of the estimation of energy consumption.
In Sect. 2, we explain how to estimate the net demand of the depot integrating electric light-duty trucks and Sect. 3 we present the model for power flow calculation. The result of the power flow calculation and the effect of electrifying the trucks on the voltage variation are evaluated in Sect. 4.

2 Estimation of net demand of depot

In this section, we explain how to estimate the net demand at the depot, introducing electric light-duty trucks for distribution delivery. In the estimation process, we set the following two cases:

1. The depots try to minimize the electricity cost by scheduling the charging trucks with EMS.

2. The trucks charge after completing their delivery.

Subsection 2.1 explains the common settings for these two cases, and subsection 2.2 formulates the optimization problem to minimize the electricity cost in case 1. Subsection 2.3 shows the estimation of the net demand for the two cases.

2.1 Common settings

The trucks were assumed to be operated under the timetable in Fig. 1. The trucks make deliveries in the following time slots: 8:00 a.m. to 12:00 p.m., 1:30 p.m. to 6:00 p.m., and 7:00 p.m. to 9:00 p.m. The trucks stay at their depot except for these time slots and can be connected to the chargers.

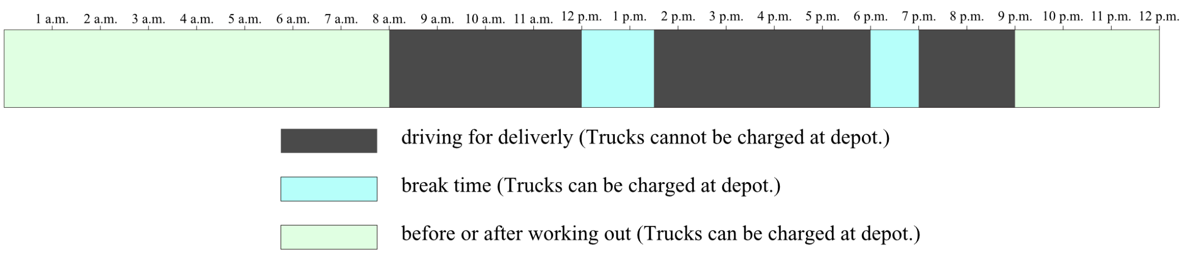


Figure 1: Timetable for electric light-duty trucks introduced to the depot.

Each depot was assumed to have three types of component: building, photovoltaics (PVs), and normal chargers. For estimating the net demand at each depot, we used the open data of energy consumption at the building [4] and power production from PVs [5]. The parameters for these components are listed in Table 1.

Table 1: Parameters for estimating net demand at each depot

Parameter	Value
Number of trucks	30
Rated power of each charger (P_{cap})	6kW
Energy capacity of each truck (E^{i}_{cap})	40kWh
Energy efficiency of each truck (η)	1.8kWh/km
Driving mileage per day (D_{day})	60km
Length of time block (Δt)	30 min

2.2 Optimization problem with EMS

Each depot was assumed to buy and sell electricity in an electricity market when it utilized EMS. In this subsection, we formulate the optimization problem to minimize the net electricity cost by scheduling the charging of trucks with EMS.

The net electricity cost is the objective function and is calculated as Eq. (1),

$$obj = \sum_{d,h} (\mu^{\text{buy}}_{d,h} \times E^{\text{buy}}_{d,h} - \mu^{\text{sell}}_{d,h} \times E^{\text{sell}}_{d,h}) \, . \tag{1}$$

$\mu^{\text{buy}}_{d,h} \times E^{\text{buy}}_{d,h}$ and $\mu^{\text{sell}}_{d,h} \times E^{\text{sell}}_{d,h}$ correspond to the cost of buying electricity and the income from sold electricity at the h-th time block on the d-th day, respectively.

$\mu^{\text{buy}}_{d,h}$ and $\mu^{\text{sell}}_{d,h}$ are respectively the prices for purchasing and selling 1kWh of electricity at each time block.

$E^{\text{buy}}_{d,h}$ and $E^{\text{sell}}_{d,h}$ are respectively the amounts of purchased and sold energy at each time block.

In addition to $E^{\text{buy}}_{d,h}$ and $E^{\text{sell}}_{d,h}$, the optimization problem also involves two other variables: $S^{i}_{d,h} \in \{0, 1\}$ and $C^{i,j}_{d,h} \in \{0, 1\}$. $S^{i}_{d,h}$ indicates whether the i-th truck is parked at the depot (1: parked, 0: not parked) and $C^{i,j}_{d,h}$ indicates whether the i-th truck is charged with the j-th charger at the depot (1: charged, 0: not charged).

These variables were optimized under five constraints: supply–demand balance, contracted power, normal charging capacity, the SOC of trucks, and delivery mileage.

The energy supply and demand at the depot must be balanced, and the relationship is given as Eq. (2),

$$E^{\text{buy}}_{d,h} + E^{\text{pv}}_{d,h} = E^{\text{sell}}_{d,h} + E^{\text{bldg}}_{d,h} + \sum_{i,j} E^{i,j}_{d,h} \, . \tag{2}$$

The left and right sides correspond to the energy supply and demand at the depot respectively. $E^{\text{pv}}_{d,h}$ is the amount of energy generated by the PVs, $E^{\text{bldg}}_{d,h}$ the amount of energy consumed by the depot building. $E^{i,j}_{d,h}$ the total amount of energy consumption, which appears upon charging the i-th truck with the j-th charger.

The amount of energy purchased at each time block is restricted by the contracted power as Eq. (3),

$$E^{\text{buy}}_{d,h} \leq P_{\text{con}} \times \Delta t \, . \tag{3}$$

P_{con} is the contracted power of each depot and the load at each depot can not exceed it. Δt is the length of the time block.

$E^{i,j}_{d,h}$ is limited by the constraint of the normal charging capacity as follows,

$$E^{i,j}_{d,h} \leq P_{\text{cap}} \times S^{i}_{d,h} \times \Delta t \, . \tag{4}$$

P_{cap} is the rated power of the normal chargers. For example, if the i-the truck is not parked at the depot, $E^{i,j}_{d,h}$ is limited to $P^{j}_{\text{cap}} \times 0 \times \Delta t = 0\text{kWh}$

The SOC of trucks changes owing to the charging at the depot and the driving for the delivery. The SOC of the i-th truck at each time block ($soc^i_{d,h}$) is constrained as Eq. (6),

$$soc^i_{d,h} = soc^i_{d,h} + \frac{\sum_j E^{i,j}_{d,h} - E^i_{d,h}(1 - S^i_{d,h})}{E^i_{\text{cap}}} \times 100\,, \tag{5}$$

$$= soc^i_{d,h} + \frac{\sum_j E^{i,j}_{d,h} - \eta D^i_{d,h}(1 - S^i_{d,h})}{E^i_{\text{cap}}} \times 100\,. \tag{6}$$

$E^i_{d,h}$ indicates the energy consumption due to the driving for delivery at each time block and can be calculated by drividing the length of mileage at each time block by the energy efficiency of the truck.
The driving mileage per day was set and each truck must satisfy it as Eq. (7),

$$\sum_{h,i} D^i_{d,h} \times (1 - S^i_{d,h}) \geq D_{\text{day}}\,. \tag{7}$$

The net demand for the case 1 was estimated by solving the optimization problem for one year, which is formulated in this subsection. We would like to remark that the EMS was assumed to predict the energy consumption and energy production at the depot. Therefore, the prediction error was not considered in the estimation process.

2.3 Estimated net demand and energy consumption at each depot

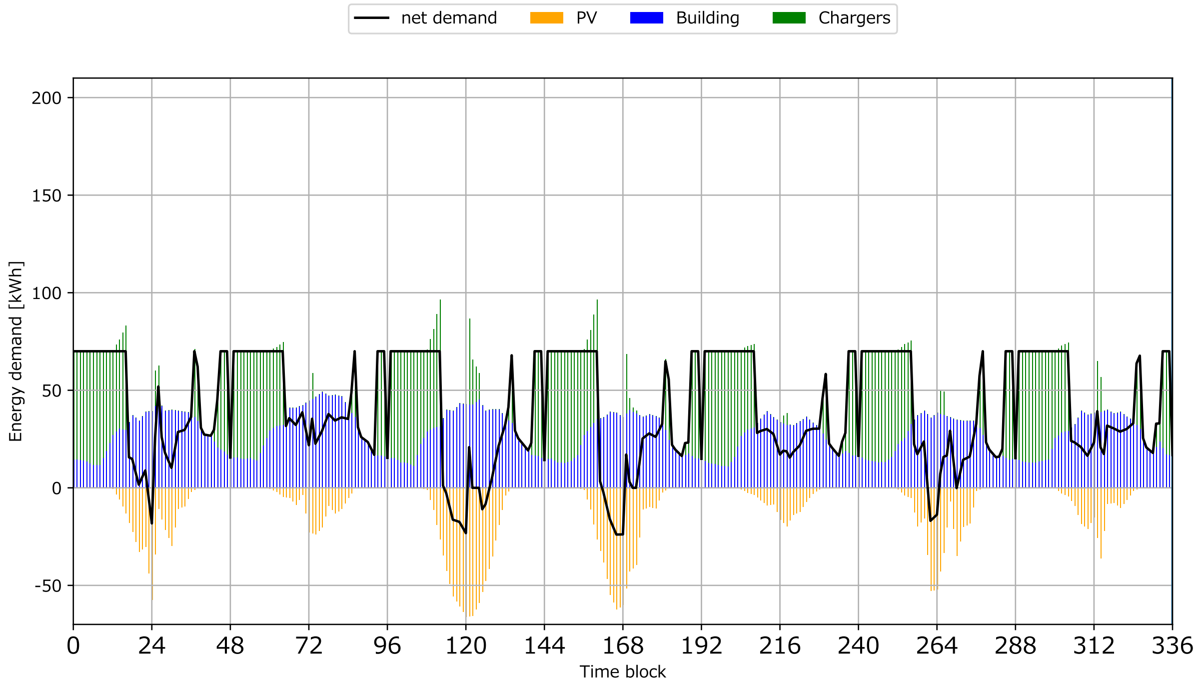
Figure 2 shows the estimation results of the net demand. The result was shown for the periods when the estimated energy consumption was highest, and the season was summer.
The difference appeared at the peak between the two cases in Fig. 2. The peaks appeared at around 9 a.m. for the case in which EMS was applied. On the other hand, the energy consumption was saturated around 70kWh and the peaks were suppressed. The dominant factor for the saturation is the constraint of contracted power.

3 Model for power flow calculation

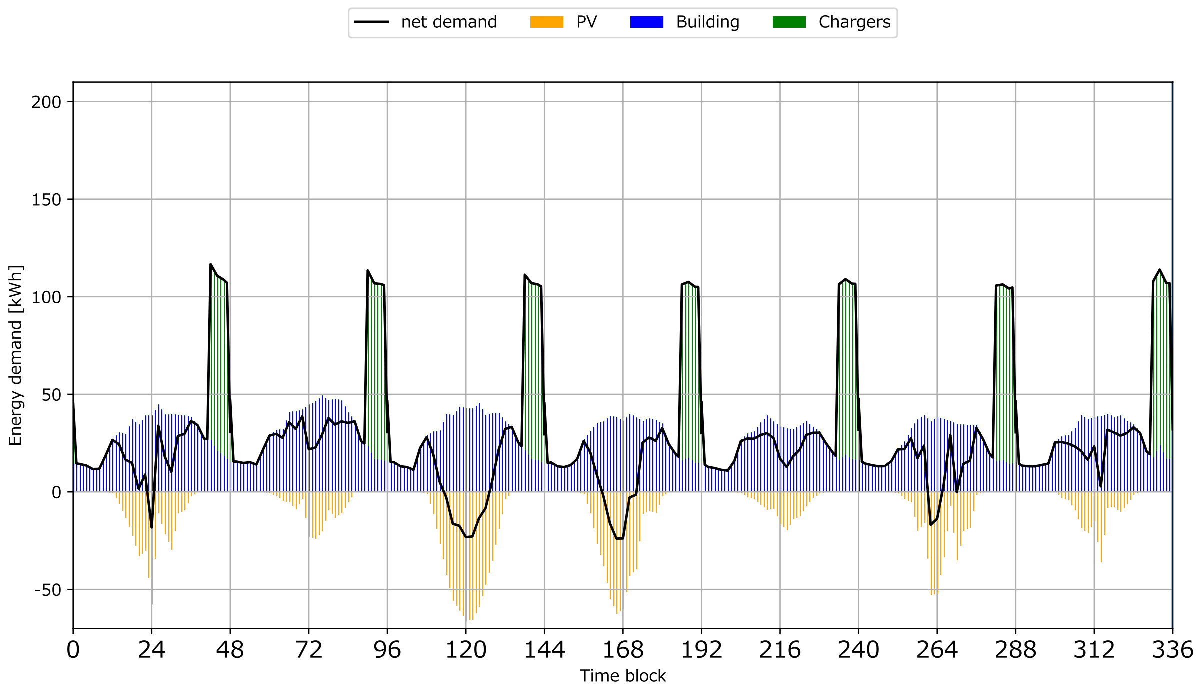
In this section, we explain how to construct the model of a distribution network for the power flow calculation, which aimed to evaluate the effect of electrifying light-duty trucks on the voltage variation in ditribution network.
We constructed the model of the distribution system based on one of the open models [6]. And the depots described in chapter 2 was integrated into the base model.

3.1 Base model of distribution network

We chose a general distribution model in the Japanese residential area [6] as a base model. Fig. 3(a) shows the topology of the distribution model as the base model.
There was the distribution substation and the 6.6kV-class distribution network was spread under the substation. The nodes of the network corresponded to middle-voltage poles, and the loads or generators were connected to the nodes.
Some of the nodes were equipped with pole mounted transformers. Low-voltage lines were connected to the pole mounted transformers, which are not described in Fig. 3(a). The transform ratio of voltage at each pole mounted transformer was fixed at 6750V/105V.
The daily total load in the base model is shown in Fig. 3(b). The load peaks at night; such a curve often appears in residential areas.
The total load was disaggregated and assigned to each node. In this process, the loads and generators were assumed to be distriubuted to the distribution network uniformly.

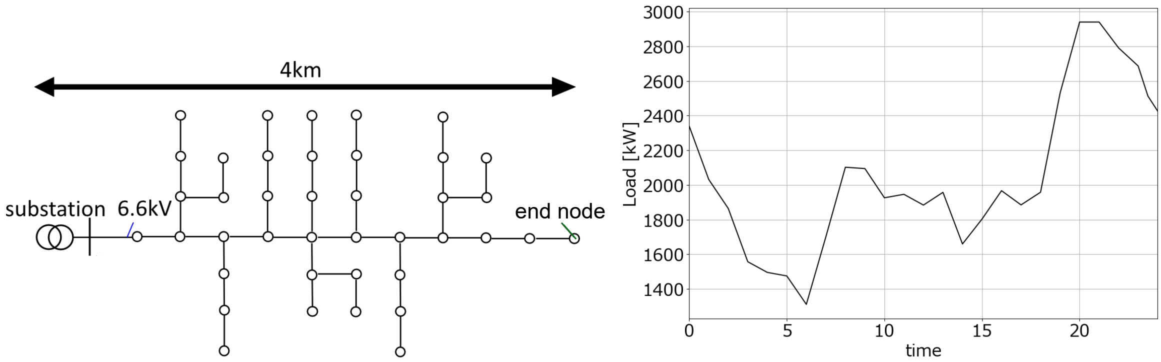


(a) with EMS



(b) without EMS

Figure 2: Estimated net demand in each depot over 7 days.



(a) Topology of base model (b) Total load of base model

Figure 3: General distribution model in Japanese residential area, which was selected as the base model of the distribution network in this study.

3.2 Integration of depots as load into base model

To consider the effect of the charging trucks at depots, the load at depots should be integrated into the base model. In the integration process, the depots were assumed to be connected to the nodes around the end node of the network shown in Fig. 3(a). This is because the load variation at the end node critically affects the voltage variation in the distribution network.

The time series data on the load at depots can be transformed from the estimated net demand shown in Fig. 2 by calculating Eq. (8).

$$P^{\mathrm{dep}}_{d,h} = \frac{E^{\mathrm{buy}}_{d,h} - E^{\mathrm{sell}}_{d,h}}{\Delta t} \tag{8}$$

$P^{\mathrm{dep}}_{d,h}$ is the average load of the depot at the h-th time block on the d-th day.

4 Analysis of voltage drop

The power flow equations can be formulated for the distribution network, whose construction was discribed in in Sect. 3. In the process of power flow calculation, the power flow on each branch and the voltage at each node were given as the solution of the power equations.

In this section, we discusses the impact of electrifying the light-duty trucks for distribution delivery on the voltage variation on through power flow calculation. A comprehensive analysis tool for distribution system with distributed generations and customer system [7] was used for the power flow calculation.

Figures 4 and 5 show examples of power flow calculation results. The day on which the peak loads were the highest over 7 days was picked up in these figures.

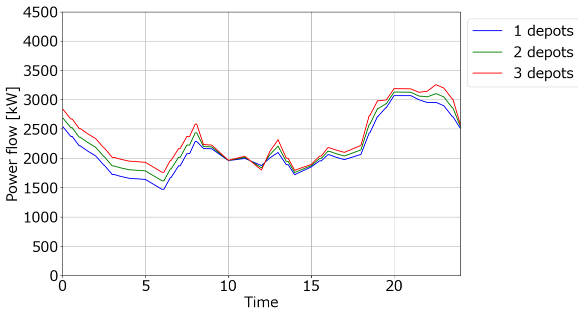
Figure 5 shows the primary voltage of the pole mounted transformer at the end node, and the orange lines corresponds to the limitations[1].

The voltage dropped with the increase in power flow on the distribution network. In particular, the voltage dropped below 102V when three depots without EMS were integrated into the distribution network.

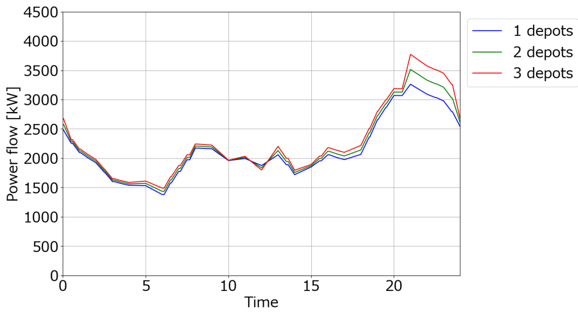
On the other hand, the voltage drop was suppressed when the depots with EMS were integrated into the distribution network. This was because the peak load was suppressed by EMS.

The voltage distribution at the end node appeared like Fig. 6 over seven days. Even if the number of depots increased, the voltage did not drop significantly when the depots applied EMS. The results indicated that the EMS contributed to voltage control in the distribution line.

[1]In Japan, strict regulations apply only to low voltages. The voltage supplied to low-voltage customers must be maintained between 95V and 107V. The lower limit was set at 102V with the consideration of the voltage drop in pole mounted transformers and the low-voltage distribution lines.

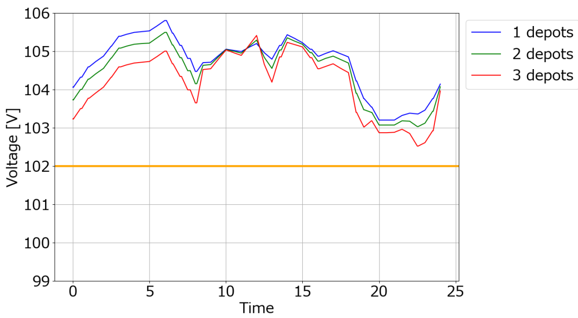


(a) Integrating depots with EMS

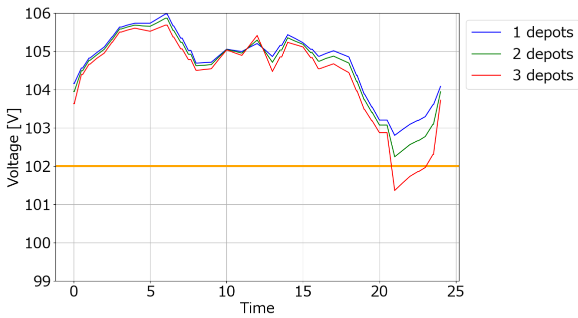


(b) Integrating depots without EMS

Figure 4: Power flow from the substation. The power flow increased with the integration of the depots, which introduced electric light-duty trucks.

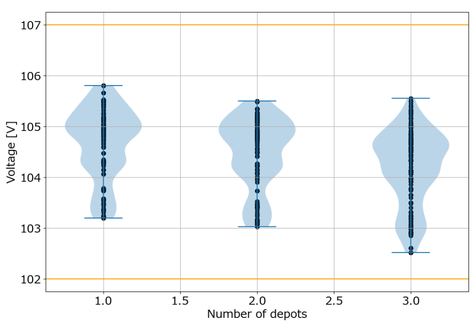


(a) Integrating depots without EMS

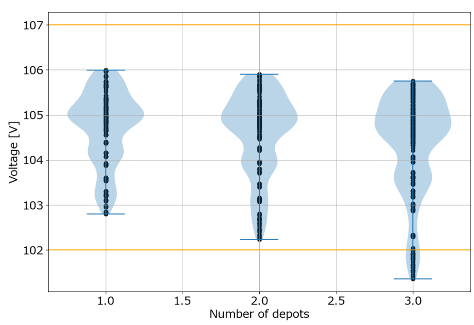


(b) Integrating depots with EMS

Figure 5: Calculated daily changes in voltage at the end node of the distribution line.



(a) Integrating depots without EMS



(b) Integrating depots with EMS

Figure 6: Voltage at the end node over 7 days.

5 Conclusion

In this study, we targeted the electrification of light-duty trucks for distribution delivery. First, we estimated the net demand at the depots. Second, we analyzed the voltage variation in the distribution network. The net demand at the depots were estimated for two cases. High peaks appeared around 9 p.m. when the trucks charged after completing their deliverly. On the other hand, the peaks were suppressed by scheduling the timing of charging the trucks with EMS.

It was found that the voltage on the distribution network dropped because of the charging of trucks at the depots. However, it was also suppressed by integrating EMS into the the depots. If the systems on the side of DSOs can cooperate with EMSs at each depot, it will facilitate the electrification of commercial vehicles without placing additional strain on the power grid.

Here, we have to emphasize the fact that the contribution of EMS strongly depends on its strategy. EMS can suppress the electric cost for the depots and the result may change depending on the price plan and the contracted power.

Moreover, in this study, we assumed that EMS can accurately predict the energy consumption and power production at the depots. However, the prediction may contain errors and how the errors affect the outcome has not been studied yet.

Acknowledgments

This presentation is based on the results obtained from a project commissioned by the New Energy and Industrial Technology Development Organization (NEDO) (JPN P21028).

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Presenter Biography

Toko Mannari received and Ph.D. degrees in electrical engineering from Kyoto University, Japan in 2020. She joined Central Research Institute of Electric Power Industry (CRIEPI) in 2021 and she has been researching the integration of electric vehicles into distribution systems.