Regular Paper

A Study on Power Distribution Method Using Electric Vehicles

Masashi Saito*, Wataru Kunimatsu*, Hikaru Akutsu**, Chiaki Kojima**,
Kazutoshi Sakakibara†, Hironao Kawamura‡

* Graduate School of Engineering, Kanazawa Institute of Technology, Japan
** Department of Electrical and Electronic Engineering, Toyama Prefectural University, Japan
† Department of Data Science, Toyama Prefectural University, Japan
‡ Innovation Laboratory, Hokuriku Electric Power Company
msaito@neptune.kanazawa-it.ac.jp, b1846432@planet.kanazawa-it.ac.jp
hikaru_akutsu@pu-toyama.ac.jp, chiaki@pu-toyama.ac.jp, sakakibara@pu-toyama.ac.jp
h.kawamura@rikuden.co.jp

Abstract - We have developed a simulator to establish energy management algorithms for realizing power distribution over wide areas using electric vehicles. This simulator is for a service called a virtual power distribution network, which not only eliminates waste power from solar power generation, but also cuts peak power demand.

We have set up the simulation with the area being 20km square, with roads running north-south and east-west every 1km. This area is divided into three categories: commercial, industrial, and residential. We have evaluated and verified changes in power generation and demand throughout the day by setting use cases for power generation, demand, and power storage systems and simulating power transportation using thousands of electric vehicles.

Simulation results show the amount of electricity purchased from the grid in the industrial area could be reduced by 92%, by using power transmission part time job use case (EV part-timer), which transmits power actively using price differences in buying and selling. Using this mode, power distribution becomes very active, but this requires much more charge/discharge points. The number of required charge/discharge points increase squaring.

In this simulation, only data from the Hokuriku region is used for electricity consumption and solar power generation. By replacing these data, the feasibility of power distribution can be verified for all regions, showing that a wide variety of simulations in social systems is possible.

Keywords: Power Distribution, EV, Wide Area Simulation

1 INTRODUCTION

The introduction of renewable energy is accelerating toward a decarbonized society, and photovoltaic power generation (PV) is attracting attention. However, due to the shutdown of some power plants due to natural disasters such as earthquakes, and the increased use of air conditioning equipment due to falling temperatures, electricity demand has increased, and it is becoming an issue that daily peak demand for electricity cannot be met [1] [2].

On the other hand, the amount of electricity generated by renewable energy in Japan increased about four times in fiscal 2020 compared to fiscal 2012, resulting in a surplus of electricity supply, and output control from April to September 2023 reached 194 times, about three times the previous year. In areas with high electricity demand, such as the Tokyo metropolitan area, requests to save electricity were made, and there were concerns about a shortage of power supply. Such unstable supply and demand of electricity could lead to power outages.

In addition, there is a situation where new construction of power transmission network facilities is not progressing due to opposition from surrounding areas, and measures to deal with the aging of existing power transmission networks are also a heavy burden [3] (Fig. 1).

The Japanese government plans to increase the proportion of renewable energy to 36-38% in FY2030, which is about double the proportion in FY2019, and has estimated that 6 trillion to 7 trillion yen will be needed to develop the power grid in 2022 [4]. Therefore, it can be said that conventional power generation and transmission capacity is not enough to meet the demand.

Sustainable and stable supply of energy, including electricity, as well as decarbonization and low carbonization are important issues, and from this perspective, the introduction of renewable energy in the power sector and the introduction of EVs (electric vehicles) in the transportation sector are expanding. EVs are equipped with large-capacity storage batteries as a power source, so they are expected to be used not only as mobile vehicles but also in the power sector. Assuming that the penetration rate of EVs increases to 50% of new car sales by 2050, it is estimated that the power

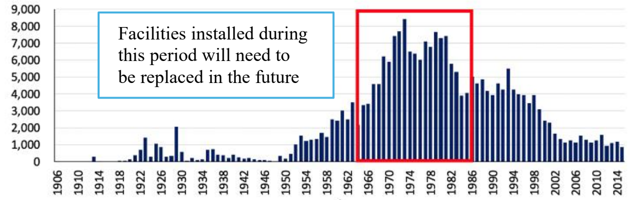

Figure 1: Distribution of Existing Steel Towers by Manufacturing Year in 2015

consumption used by EVs at that time will increase to 46.3 billion kWh, up 164.3% from 2016 [5].

EVs are equipped with large-capacity storage batteries as a power source, so they are expected to be used not only as mobile vehicles but also in the power sector. Representative examples include (i) providing energy services to the power grid and consumers by connecting EVs to the grid and charging/discharging their storage batteries, and (ii) serving as an emergency power source during disasters or grid blackouts.

In this research, to realize the role of (i) above, we have developed a simulator that uses EVs to transport electricity to places where there is a power shortage. Using the developed simulator, we report the results of evaluating and verifying the simulation results to see whether a power transmission system can be established without changing the current grid system.

2 RELATED WORKS

Ichii et al. [6] examined the possibility of EVs replacing privately operated power lines as a means of making up for power shortages in smart towns, which is an important issue in the use of renewable energy. As a result, the possibility of EVs replacing privately operated power lines was low in satellite smart towns (SSTs) close to distributed power sources, but in small, remote SSTs, the transportation costs of EVs were lower than those of privately operated power lines, indicating the possibility of EVs replacing privately operated power lines. In addition, with improvements in electricity self-sufficiency and advances in DC power supply technology, it is expected that costs will be reduced by using EVs. It was also suggested that there is a high possibility of low-cost use of EVs for electricity transportation. This suggests that costs can be reduced for SSTs by having EVs take on the role of electricity transportation, and that transmission separation could be an opportunity to promote the use of renewable energy.

Tanoue et al. [7] aimed to build a support system for power transportation by EVs. Although the power consumption characteristics of EVs vary depending on the driving state, distance, and altitude; to facilitate the use of geographic information systems, they proposed a method to estimate the power consumption of EVs while driving by separately expressing the power consumption of distance and altitude difference. As a result, they derived an equation for estimating the power consumption of EVs while driving using geographic information. They also showed that it is possible to visually grasp the EV power by visualizing it using the derived estimation equation.

Urabe et al. [8] designed a new EV infrastructure system that realizes peak shift of power by providing power (batteries) to users within the power supply area using EVs and considered the leveling of power demand. As a result, they showed the effectiveness of efficiently using the batteries provided to users from three perspectives: the optimal number of EV infrastructure systems to be placed within the area, the optimal facility placement of EV infrastructure systems within the area, and a plan for providing power to users within the area using the EV infrastructure system.

Murakami [9] used agent-based simulation to examine the problem of power load concentration due to the spread of electric vehicles (EVs). He showed that random charging start times can sometimes achieve high power load leveling effects. He showed that autonomous information exchange and interactions among EV agents can achieve higher power load leveling. He focused on information exchange within small groups and suggested that power load leveling can be achieved even in large-scale systems without information exchange between independent groups.

Takagi et al. [10] focused on autonomous decentralized control that did not require additional investment in communication infrastructure and proposed two measures to mitigate the impact on the grid that reflected the distribution characteristics of daily driving distances and ensured convenience for EV users. As a result of the evaluation, it was found that the magnitude of the steep peak was proportional to the number of EVs charging at the same time, so along with the EV penetration rate, how frequently EV users charge was also an important factor. However, since the frequency of charging depended on various uncertain factors such as the battery capacity of EVs that would become more widespread in the future and the specifications of chargers, it was shown that even under the conditions assumed in this paper where charging impacts were most likely to occur, it was possible to mitigate the peak due to EV charging load by adopting a quadratic function case, etc.

Moriya et al. [11] proposed a method of power trading using virtual power plants in smart grids and the use of PHEVs and EVs as storage batteries to reduce peak power demand across the entire power grid, but they did not consider the driving of PHEVs and EVs. They also proposed a method of power leveling that considered the driving of PHEVs and EVs. As a result, when comparing timer charging and bottom charging, it was found that timer charging had a greater leveling effect when there were many EVs, and they showed that the power load could be reduced by using EVs.

Mustapha Aachiq et al. [12] considered electric vehicles (EVs) as a means of adjusting demand in homes and created a model to simulate what kind of EV battery operation would be optimal for consumers when linking EV batteries with PV systems under the electricity pricing system that will become more diverse in the future. The results showed that the impact of FIT prices on EV battery operation and the economics of each household is that when the FIT PV purchase price falls, the amount of reverse power flow is suppressed and the amount of charging from PV to EV increases. In addition, it is suggested that V2G can contribute to load leveling in the grid if a large number of PHEVs are introduced and electricity prices in homes are determined in conjunction with the marginal fuel cost of the grid.

These studies showed the possibility of transmitting power over a small area and meeting electricity demand.

In small-scale areas, it is easy to link EVs and power storage systems, and it is possible to respond to peak power demand even after power demand has increased. However, in medium-scale or larger areas, it is difficult to link EVs and energy storage systems, so it is necessary to verify whether it is possible to meet the power demand in areas with a power shortage through verification. Therefore, verification is carried out in a medium-scale area assuming an increased number of vehicles and a map of 20 km x 20 km.

In this study, we have developed a simulator based on various use cases in which EVs are charged using surplus solar power generation electricity, and in areas where there is a power shortage, EVs transport power to discharge it, and the effective use of surplus power from power transport and the EV infrastructure required to respond to peak power demand are verified. In addition, three patterns of power demand are prepared: commercial, industrial, and residential areas [13].

3 OVERVIEW OF ELECTRIC POWER TRANSMISSION USING EVs

3.1 Electric Power Transmission by EV

We have set up various use cases to realize a charging/discharging service using EVs in medium-sized area energy management and verify it using a simulator to investigate the impact on the supply and demand balance. Specifically, we have built a system in which surplus electricity generated by PV is charged into EVs that stop at charging/discharging points, and then transmitted to other charging/discharging points for discharging. An overview of power transmission is shown in Fig. 2.

3.2 Overview of Our EV Energy Management System Simulator

The EV energy management system is positioned between existing energy management (power control) systems and MaaS (Mobility as a Service) services, which will continue to develop in the future, and proposes charging and discharging services to moving EVs through road network. Figure 3 shows the overview of the EV energy management system.

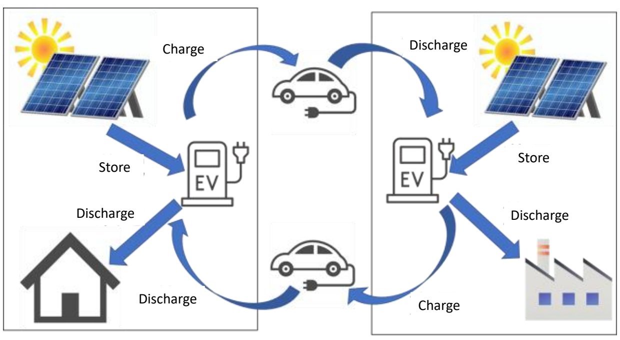

Figure 2: An overview of electricity transportation

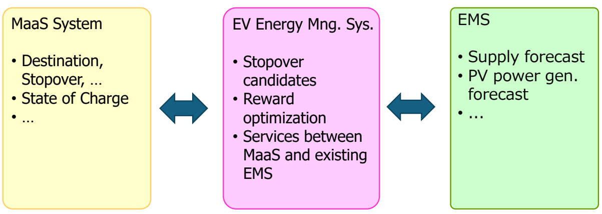

Figure 3: EV Energy Management System Overview

Unfortunately, there is no MaaS system that can be freely used in an EV energy management system, and the energy management system cannot be used. Therefore, we have developed the "EV Energy Management System Simulator (hereinafter EVEMSS)" to simulate electricity transportation. EVEMSS is composed of a vehicle information simulator instead of a MaaS system, an EV energy management system, and an existing energy management system that provides data on the grid DB that manages the power demand and PV power generation managed by the energy management system (Fig. 4). The reason why the Power Grid is connected to charging/discharging points is because the surrounding area’s electricity is provided via the charging/discharging point.

By using EVEMSS to investigate and analyze the impact in various use cases, it is possible to use it as a basic tool for verifying and proposing new power supply systems and their services.

The EV energy management system is a subsystem that realizes customer value by customers who drive EVs stopping at places called charging/discharging points. This subsystem provides a buying and selling intermediation service by effectively utilizing surplus electricity generated by solar power generation, realizing a win-win relationship in which EV owners can purchase cheap electricity and PV owners can sell waste electricity that they are forced to discard. Through such intermediation, we hope to determine the possibility of creating new service businesses.

3.3 EVEMSS System Configuration

The system configuration of the EVEMSS is shown in Fig. 5. The vehicle information simulator drives the vehicle using

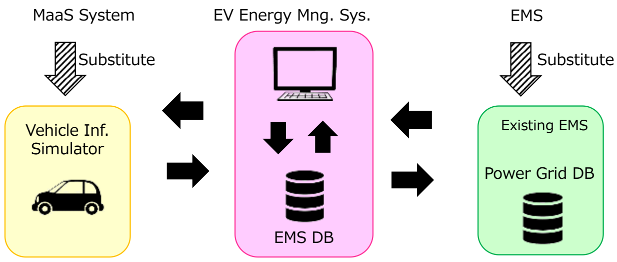

Figure 4: EV Energy Mng. System Simulator Overview

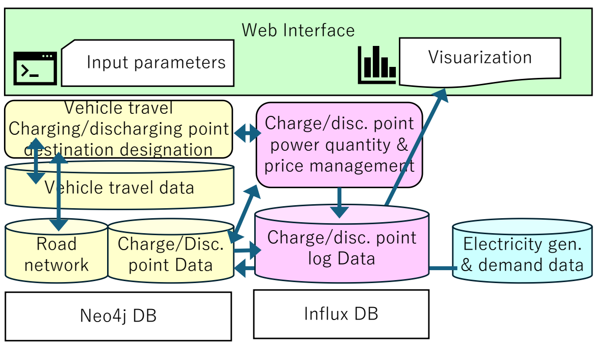

Figure 5: EVEMSS System Configuration

data for vehicle movement, road networks, and charging/discharging point data. When charging/discharging becomes necessary, it queries the EV energy management system to determine the route and destination. The EV energy management system manages the amount of electricity and buying/selling prices at charging/discharging points, as well as managing the power logs of the charging/discharging points. The existing energy management system stores data on the amount of electricity generated and demand at each location.

3.4 Road Network in EVEMSS

The system has been currently built assuming a Manhattan model road network. A tertiary mesh code is used for this purpose. The distance of a tertiary mesh code is not constant because the Earth is a sphere, but in the Hokuriku region it is 926 m north to south and 1,118 m east to west. EV operation is simulated on a 20 x 20 grid road network divided into tertiary meshes [14].

The roads defined above have a graph (network) structure. In order to make it possible to represent any road in any location, we are using Neo4j, a NoSQL database that makes it easy to model graph structures.

We assume that the data on charging and discharging points is held by the MaaS service. Each node stores the amount of battery power held in the battery in that area, the price at the time of buying and selling and so on.

3.5 Visualization of EVEMSS

In order to simplify the execution of EVEMSS and the evaluation of the simulation results, a web-based front end has been developed, which allows the selection of input data files, the display of the overall simulation results, and the detailed examination of individual results interactively. This makes it possible to execute simulations of multiple scenarios by simply replacing the data in EVEMSS.

Figure 6 shows an example of charging/discharging point power amount.

Vehicle information is set one by one, including the vehicle identifier, departure time, charging/discharging behavior, initial battery value, departure point, multiple intermediate destinations, and destination.

Electricity generation and demand are set every 30 minutes.

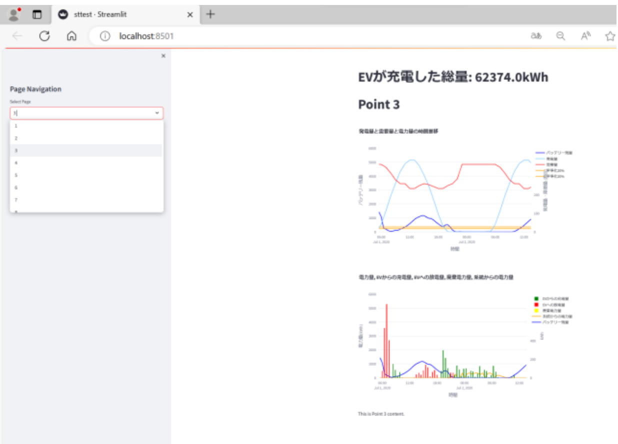

Figure 6: Visualization of EVEMSS

4 SIMULATION SETTINGS

4.1 Road Network and Charging/ Discharging Point Settings

We assume the Manhattan model for the road network as explained in Section 3.4. In addition, we arrange the charging /discharging points as power demand locations, with commercial areas, industrial areas, and residential areas. We also set up 16 charging/discharging points as representative locations of 5km square at the center of the area (Fig. 7).

Each charging/discharging point has 900 kWh power batteries, which are used as a charging and discharging infrastructure in each region as a grid network. In addition, like a typical gas station, multiple-bidirectional chargers are set up to be available, and in this study, up to six units can be traded at one charging/discharging point.

4.2 Power Generation and Demand Setting

Regarding the use case of the power generation, demand, and storage system, the season of power generation is set to one day in summer. The day with the most solar radiation in the year is set based on data from the Japan Meteorological Agency for Kanazawa City [15], and the simulation has been performed based on that.

Power demand is created based on the power load level of the Institute of Electrical Engineers of Japan model. The specific values are created originally based on data from the Architectural Institute of Japan [16].

The amount of power generated by PV and the amount of power demand in each area are shown in Fig. 8. Simulations have been performed based on these values from now on. The graph shows the amount of power generated in blue, the power demand in residential areas in orange, the industrial

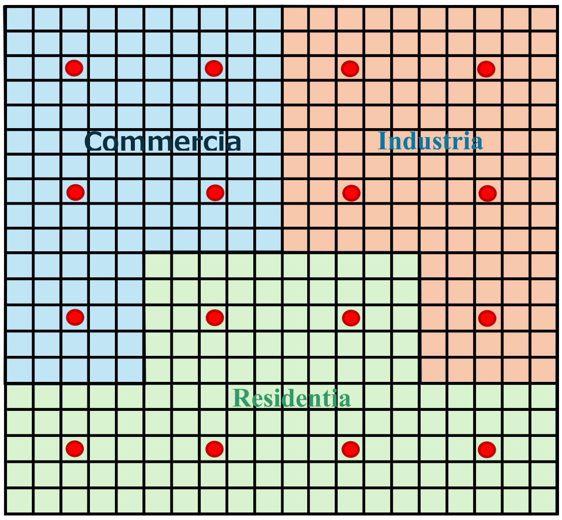

Figure 7: Road Network and Charging/Discharging Points in EVEMSS

areas in gray, and the commercial areas in yellow. In addition, the time setting is set to 5:00 a.m. to 2:00 p.m. the following day to take into account the effects of the late-night hours when power consumption is high.

4.3 Vehicle Driving and Behavior Settings

Vehicle use cases are set using data from the Japan Road Traffic Information Center (JARTIC) [17]. The settings are based on the traffic volume on Route 8 at Okyozuka in Ishikawa Prefecture, and every 10minutes in the EVEMSS the number of the traffic volume EVs start driving.

Each vehicle runs two laps of approximately 80km circumference at a speed of 40km/h. The maximum battery capacity of the EV is set at 70kWh, each EV start searching charging/discharging point at 20% of battery capacity for charging and at 95% for discharging. A discharging EV stops discharging at 20% of battery capacity.

Two patterns of EV behavioral changes are prepared for the vehicle's behavior settings. The first is a vehicle that prioritizes distance when heading to a charging/discharging point. The second is a EV part-timer mode. A distinctive feature of this vehicle's behavior settings is that it does not sell power unless the selling price when discharging is at least 10 yen higher than the selling price when charging.

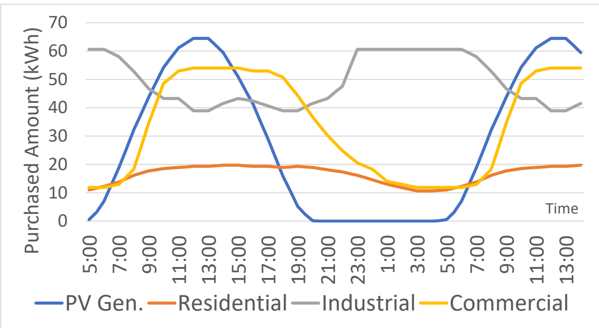

Figure 8: The Amount of Power Gen. by PV and the Amount of Power Demand of Each Area

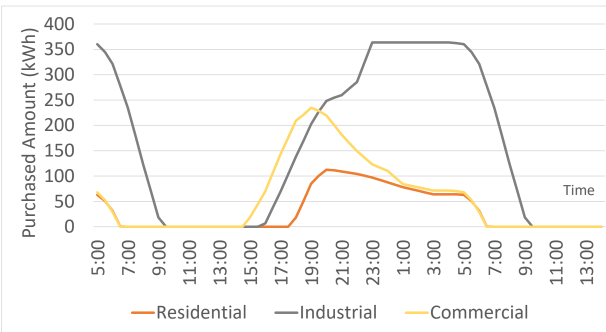

Figure 9: Use of PV Power Generation

5 SIMULATION RESULTS

5.1 Use of PV Power Generation and Battery

Prior to conducting the simulation, electricity is purchased from the grid by time based only on the amount of electricity generated by PVs, and the results are shown in Fig. 9.

Commercial areas need to purchase 3,852 kWh of electricity from the grid, industrial areas 10,822 kWh, and residential areas 2,906 kWh.

The results in Fig. 9 show that the amount of electricity purchased from the grid is concentrated from the evening through the night, and it can be said that the bias in the time periods for electricity purchases makes it impossible to stabilize the electricity supply and demand balance.

Next, we simulate with PV power generation and batteries. Simulation results are shown in Fig. 10. The presence of the battery is enough to cover the electricity needs of the residential area. However, the industrial area needed to purchase 7,572 kWh of electricity from the grid, and the commercial area needed to purchase 1,202 kWh. The amount of electricity purchased from the grid in the industrial area is reduced by approximately 30% compared to when there is no battery. As for the residential area, the result shows that surplus electricity is generated. It can also be seen that even with the use of the power storage system, the amount of electricity purchased during the nighttime hours is high. Therefore, it is necessary to consider measures to ensure electricity for commercial and industrial areas at late-night.

5.2 Evaluation of Electric Power Transmission by EVs

5.2.1 Evaluation Assuming EVs Account for 2.5% of Traffic Volume

The evaluation is carried out assuming that 2.5% (629 vehicles) of vehicle traffic are EVs, 50% of the EV departures are from drivers who prioritized distance, and the remaining 50% are from drivers who are driving in EV part-timer mode.

The results in Fig. 11 show that commercial areas need to purchase 588 kWh of electricity from the grid, industrial areas 2,996 kWh, and residential areas 570 kWh. It can be seen the

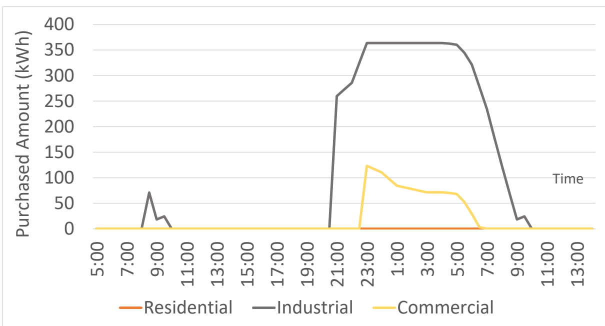

Figure 10: Use of PV Power Generation and Batteries

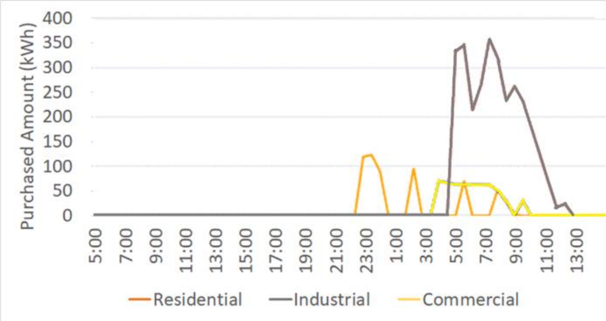

Figure 11: Use of 2.5% vehicle being EV

amount of electricity purchased from the grid in industrial areas is reduced by approximately 60% compared to when an evaluation is conducted using only the energy storage system. It also shows that the generation of surplus electricity in residential areas can be eliminated by conducting electricity transmission trading. However, it can be seen from the results that the amount of electricity purchased during late night hours has not been reduced compared to Fig.9.

5.2.2 Evaluation Assuming All 2.5% of Vehicle Traffic Volume Being in EV Part-timer Mode

The number of EVs is set at 2.5% of the vehicle traffic volume, and the evaluation is carried out assuming that all vehicles are driven by drivers using EV part-timer mode.

From the results in Fig. 12, the industrial area needs to purchase 4,551 kWh of electricity from the grid, and the residential area needs to purchase 645 kWh. It can be seen that the amount of electricity purchased from the grid in the industrial area is reduced by approximately 40% compared to when an evaluation is performed using only the energy storage system.

Effect of EV power transmission in industrial areas

We evaluate whether electricity purchases from the grid during the night and late-night hours in industrial areas can be reduced by electricity transportation and evaluated the impact of the number of EV vehicles and distance-priority mode and electricity part-timer mode shown in Table 1.

From the above results, the amount of electricity purchased from the grid in industrial areas can be reduced by using EVs for power transmission, but the effect of power transmission decreases when the number of vehicles exceeds a certain level. Therefore, a simulation is performed with the following settings:

Table 1: Amount of Electricity Purchased from the Grid Using both Modes and Part-Timer Mode

The number of Vehicles	Purchased Amount Both Modes	Purchased Amount Part-Timer Mode
629	2,996 kWh	4,551 kWh
1,246	2,085 kWh	2,585 kWh
2,492	3,722 kWh	1,403 kWh
3,738	3,482 kWh	3,607 kWh

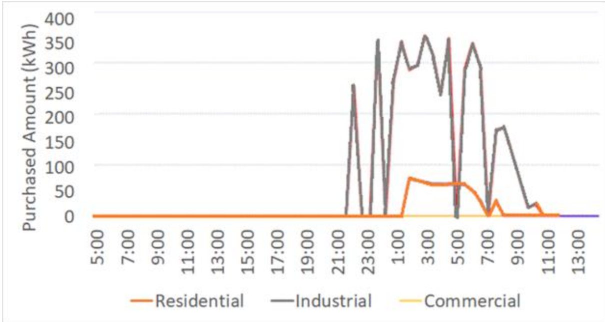

Figure 12: Use of EV Part-timer Mode

(1) When transporting electricity to industrial areas, charging is not performed in the industrial areas, only discharging is performed,
(2) The price is changed by time of day, and the behavior of the electric power part-time mode vehicles is changed.

By implementing these measures, the amount and timing of electricity purchased from the grid in industrial areas and other areas changes, but it does not necessarily work well. The application of a more sophisticated algorithm is necessary.

5.3 The Number of Vehicles and Discharge Amount

Figure 13 shows how much discharge is possible depending on the number of vehicles being charged and discharged simultaneously. Kanazawa city has approximately 80,000 vehicles, of which 4,000 vehicles are in operation if the vehicle utilization rate is 5%. If the scale of Kanazawa

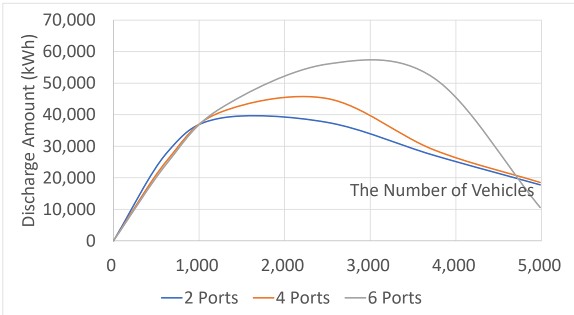

Figure 13: Relationship Between the Number of Vehicles and Discharge Amount

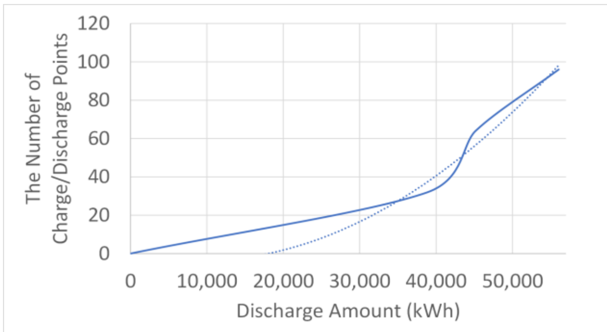

Figure 14: Required Chage/Discharge Points for Discharge Amount

city and the EV energy management system simulator are combined, the number of vehicles is approximately 3,400 vehicles if the vehicle utilization rate is 5%, so it can be said that an infrastructure environment capable of accommodating at least this number of vehicles is necessary.

Figure 14 is a graph showing the maximum discharge amount versus the number of charge/discharge points. The approximation formula is expressed as follows:

$$y = 0.00000005x^2 - 0.0008x - 0.23$$

From Fig. 12 and the approximation equation, it is possible that in order to increase the amount of power transmitted, the charge/discharge points must be increased by the square of the amount of power.

6 CONCLUDING REMARKS AND FUTURE WORKS

In this study, we set up a specific use case to realize a charging and discharging service using EVs in energy management in a medium-sized area and verified it using a simulator to investigate the impact on the supply and demand balance. It is shown that by transporting electricity using EVs, surplus electricity can be reduced to 0 kWh and peak electricity demand can be cut.

In order to solve the power shortage in the industrial area at night and late at night, we evaluate it with a setting that all EV part-timer mode and no charging from the industrial area but discharging to the industrial area. This changes the amount and timing of electricity purchased from the grid in the industrial area and other areas, but it does not necessarily work well, more sophisticated algorithm is necessary.

In addition, under the current infrastructure setting, there are not enough charging places for EVs when the number of vehicles exceeds a certain level, so it can be said that a charging and discharging infrastructure suitable for the number of vehicles is necessary.

From the relationship between the number of vehicles and the amount of discharge, it is found that in order to increase the amount of electricity transmitted, the number of vehicles trading at the charging and discharging points must be increased by about the square of the amount of power amount. In the future, when verifying by increasing the number of vehicles, it can be said that the number of charging/ discharging points must be increased at the same time.

Based on the above, future issues include power leveling and incentives for vehicles.

Regarding the power demand in industrial areas, this model is for the case where the power company promotes operation at night to prevent power shortages in industrial areas. Therefore, future verification will also need to verify the case where there is a peak in power demand during the daytime when the power company's power usage shift is not implemented. This will become increasingly important in the future when power supply by PV becomes common.

As future works, we would like to conduct simulations based on more realistic road networks, vehicle driving, charging/discharging point placement and power demand, and show that it is possible to provide power transmission by EVs in specific areas, and even services such as home delivery of power by EVs. In fact, the current EVEMSS does not scale with respect to the number of EVs. In addition, from the perspective of the power company, if it becomes possible to implement measures such as leveling the supply of power and limiting the upper limit of the amount of power transmitted in the grid, we would like to aim for power transportation by EVs to emerge as a real service.

REFERENCES

[1] Ministry of Economy , Trade and Industry Japan, "Draft report on the tight electricity supply and demand situation in eastern Japan in March 2022", pp3-7 (2022).

[2] A. Nakajima et al., "Impact of the shutdown of large-scale generators due to the Great East Japan Earthquake on JEPX electricity spot prices", Proceedings of the Tohoku Branch Joint Conference of the Institute of Electrical Engineers of Japan (2012).

[3] Agency for Natural Resources and Energy, “Current energy situation and issues”, https://www.meti.go.jp/shingikai/enecho/denryoku_gas/denryoku_gas/pdf/045_04_02.pdf, (accessed Jan. 25, 2023).

[4] Yomiuri Shimbun, Electricity Crisis <2> Poor power transmission, renewable energy waste, (2023/11/21).

[5] M. Fujiyama, "Electricity consumption in 2050 will decrease by 20% compared to 2016 - Population decline and progress in energy conservation will significantly push down electricity consumption", Japan Research Institute Research Focus, No.2018-003 (2018).

[6] K. Ichii et al., "How to transport electricity to satellite-type smart towns", Urban Planning Papers, No.3, Vol.55, pp569-576 (2020).

[7] K. Tanoue et al., "Estimation of Electric Vehicle Power Transport Capacity Using Geographic Information Based on Vertical Power Cost Calculation", Proceedings of Kyushu Joint Conference of Institutes of Electrical Engineers of Japan (2015).

[8] S. Urabe et al., "Optimal Design Method of EV Infrastructure System Considering Power Demand Leveling - By Providing Batteries to Users in Power Supply Areas -", Information Processing Society of Japan, No. 3, 2012-MPS-91, pp1-7 (2012).

[9] T. Murakami et al., "Agent Simulation of Power Load Leveling When Electric Vehicles are Connected to the Grid", IEEJ Transactions on Electrical Engineering, Vol. C (Electronics, Information and Systems Division), No. 9, Vol. 133, pp1658-1662 (2013).

[10] M. Takagi et al., "Nighttime Charging Load Leveling Strategy Considering User Convenience of Electric Vehicles," IEEJ Transactions on Energy and Power Systems, Vol. 11, Vol. 134, pp. 908-916 (2014).

[11] T. Moriya et al., "Research and Use of Electricity Trading Using Virtual Power Plants in Smart Grids," Proceedings of the 75th National Conference, Vol. 1, Vol. 201, pp. 783-784 (2013).

[12] M. Aachiq et al., "Evaluation of Residential PV-EV Systems for Supply-Demand Balance of Power Systems," IEEJ Transactions on Energy and Power Systems, Vol. 1, Vol. 135, pp. 27-34 (2015).

[13] The Institute of Electrical Engineers of Japan, "Regional Supply System Model," https://www.iee.jp/

pes/ele_systems/base_model/overview/, (accessed Sep. 1, 2023).

[14] Ministry of Land, Infrastructure, Transport and Tourism, "Third Mesh Land Use Data - National Land Numerical Information", https://nlftp.mlit.go.jp/ksj/gml/datalist/KsjTmplt-L03-a.html, (accessed Jan. 25, 2024).

[15] Japan Meteorological Agency, "Search for Past Weather Data", https://www.data.jma.go.jp/stats/etrn/index.php, (accessed Sep. 1, 2023).

[16] Architectural Institute of Japan, Research Committee on Energy Consumption in Residential Buildings, "Energy Consumption Database in Residential Buildings", http://tkkankyo.eng.niigata-u.ac.jp/HP/HP/database/index.htm (accessed Jul. 1, 2023).

[17] JARTIC, "Japan Road Traffic Information Center: JARTIC", https://www.jartic.or.jp/, (accessed Sep. 1, 2023).

(Received November 14, 2024)
(Accepted August 12, 2025)

Masashi Saito received B.E. degree from Tokyo Institute of Technology in 1983, M.E. degree from Cornell University in 1992 and Ph.D. degree from Osaka University in 2006. In 1983, he joined Mitsubishi Electric Corporation and has developed engineering workstations, Internet TVs, cellular phones, car navigation systems especially for operating system extension, Internet services and distributed processing. In 2006, he moved to Mitsubishi Electric Research Laboratories as a senior principal technical staff. Since 2015, he has been a professor at College of Informatics and Human Communication, Kanazawa Institute of Technology. His current research interests include ITS, distributed systems, smart communities and smart social systems. He is a member of IEEE and IPSJ

Wataru Kunimatsu received Bachelor of Engineering from Kanazawa Institute of Technology in 2022, Master of Engineering from Graduate School of Engineering, Kanazawa Institute of Technology. He joined Hagiwara Electric Holdings Co., LTD. in April 2025.

Hikaru Akutsu received the Ph.D. degree in engineering from Nagaoka University of Technology in 2020 and joined DAIHEN Corporation in the same year. In 2023, he became an assistant professor in the Faculty of Engineering at Toyama Prefectural University. He is engaged in research on the control of distributed power supply and demand networks.

Chiaki Kojima received Ph.D. degree in informatics from Kyoto University in 2007. In the same year, he joined the Department of Information Physics and Computing, the University of Tokyo as an Assistant Professor. In 2017, he joined the Department of Electrical and Computer Engineering, Toyama Prefectural University as a Lecturer. From 2020, he is currently an Associate Professor of the Department of Electrical and Electronic Engineering of the same university. He is engaged in research on system control theory and its applications to power and energy. He is a member of the Society of Instrument and Control Engineers, the Institute of Systems, Control and Information Engineers, the Institute of Electrical Engineers of Japan, and the IEEE CSS/PES/CASS.

Kazutoshi Sakakibara received his PhD in Engineering from Kobe University in 2004. He was an assistant professor from 2004 to 2008, a lecturer from 2008 to 2013 at Ritsumeikan University, and an associate professor from 2013 to 2024 at Toyama Prefectural University. He is a professor at Toyama Prefectural University. His present research interests include system modeling, emergent systems, and the development and application of optimization and machine learning algorithms. He is a member of SICE, ISCIE, SSJ, ISIJ, JSBA, and IEEJ in Japan.

Hironao Kawamura graduated from the Department of Electrical and Information Engineering, Faculty of Engineering, Kanazawa University in March 1998. He joined Hokuriku Electric Power Company in April of the same year and has been engaged mainly in the study of lightning protection design on transmission systems. He is currently affiliated with the company's Innovation Laboratory. He focuses on the planning of research and development. He holds a Ph.D. in Engineering.