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Versatile Modeling Platform for Cooperative Energy Management Systems in Smart Cities

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***Abstract*—With growing attention to sustainability and recognition of the impact of global warming problems, energy supply and consumption have become critically important. This paper presents the construction of a modeling platform accommodating cooperative energy management systems (EMSs), which virtually produces the model of a smart city with a distribution network (DN) by using a wide range of data obtained from the real world. The platform involves models of various EMSs, governing the operation of a power system or controlling consumer-installed devices, and simulating the power flow, electrical losses, and voltage in the DN. In addition, indices measuring the sustainability of the model city, such as CO_2 emission, are estimated from scenarios, for example, photovoltaic system installation, electric vehicle penetration, etc. The results can be visually displayed and the platform is highly versatile and applicable to various types of issues associated with smart cities. Two case studies are presented in detail.**

***Index Terms*—Smart city, smart grid, energy management system, modeling platform, PV/EV hosting capacity, CO_2 emission, energy self-sufficiency, power quality.**

NOMENCLATURE

Acronyms

BEMS	Building energy management system.
CPS	Cyber-physical system.
DER	Distributed energy resources.
DN	Distribution network.
DR	Demand response.
EMS	Energy management system.
EV	Electric vehicle.
GEMS	Grid energy management system.
HEMS	Home energy management system.
LV	Low voltage (100-200[V]).
MV	Medium voltage (6,600[V]).
OLTC	On-load tap changer.
PV	Photovoltaic power system.
RES	Renewable energy sources
SVR	Step voltage regulator.
TN	Transmission network.
TOU	Time-of-use.
ZEB	Zero-energy building.

I. INTRODUCTION

WITH growing attention toward sustainability and the recognition of the impact of global warming problems, energy supply and consumption have become critically important issues. For energy supply, encouraging the use of renewable energy sources (RESs) is a central policy throughout the world; especially, photovoltaic and wind power generations have been receiving large investments and are expected to be primary resources in the future energy generation mix. In addition, the current trend requires innovation on the consumption side with new technologies for more efficient use of energy. Firstly, in addition to the increasing power generation from RESs, some energy consuming necessities of human life will be or are being electrified, such as automobiles and heat-pump-based water heaters, to reduce primary energy consumption. Secondly, energy storage devices such as batteries are expected to mitigate fluctuations from variable RESs as well as support load leveling and emergency self-power supply. Thirdly, electricity consumption itself will become a controllable resource, typically operated according to orders or incentives from the power system operators. This mechanism,

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called demand response (DR), has been introduced in many countries to provide an alternative method for supply-demand balance of the electrical power system. All the aforementioned aspects indicate that with greater distributed energy resources (DERs) the consumer acts more as a "prosumer," not only consuming but also producing electricity. For the consumer, the objective of the DERs is to maximize some benefit, e.g., to minimize their energy bill. This will require an energy management system (EMS) at the consumer level.

On the other hand as the number of DERs grows, power system operators must integrate and control DERs to maintain the supply quality, such as frequency and voltage standards. An EMS, termed here the grid energy management system (GEMS), is necessary for power system operators to achieve this objective properly. From the viewpoint of the entire electric power system, the difficulty lies in the fact that the objective of power system operators generally differs from that of consumers regarding the application of DERs; namely, competing objectives co-exist. The solution to this complicated problem depends greatly on energy policy and must be addressed at the whole system level.

Another consideration is the wide variety of data required. EMSs on the demand side monitor the state of consumer devices, collect data, perform computation, and then send commands to achieve optimal operation. In contrast, GEMS primarily monitors parameters that represent the state of the grid, and determines how to operate available devices to maintain system reliability. In order to achieve overall optimal performance, data exchange among relevant EMSs and proper algorithms for computation at each EMS are required. In this sense, a smart city requires a cyber space of multiple EMSs interacting with each other to realize the optimal control of the grid as well as various facility and devices simultaneously, which determines the optimal operation of real facility and devices, and can be regarded as a cyber-physical system (CPS).

Based on the aforementioned understanding, this paper proposes a highly versatile platform to generate realistic models of smart cities, considering the physical topology of a power distribution network (DN), PV generation distributed on the DN, and a load pattern originating from consumers. This enables a wide variety of functions for smart cities with high penetration of distributed and mobile energy resources, such as photovoltaic systems (PVs) and electric vehicles (EVs), as well as the diffusion of EMSs throughout the power grid, homes, and buildings.

The paper is organized as follows. Section II comprehensively overviews previous works and presents key features of our platform. In Section III, our platform architecture is introduced to indicate how evaluation of smart city and the modeling can be achieved. In Section IV, the platform and evaluation methodologies are applied to two specific cases, showing the typical examples of the approach. Concluding remarks are provided in Section V.

II. EMS FOR SMART CITIES

The EMS originates from a technical request for sophistication in the transmission network (TN) operation [1]–[14] ; the systems used in the TN control centers were forced to be sophisticated with lessons learned from several large-scale blackouts occurred in the 1970s in the US [15]. Then, particularly in the 1980s and 1990s, various functionalities and architectures [16]–[18] have been well-discussed for achieving centralized control in power systems by utilizing mainframes (e.g., see [19]–[21] for references). However, under the influence of deregulation and market liberalization, the concept of distributed and decentralized power system has been proposed [22]–[29], so that sophistication of the DN has been also required for suitable power quality control targeting local areas [23], [30]. This trend has also encouraged the evolution of system functionalities, such as state estimation [31], [32], visualization [33], [34], and system security [35]–[42], so as to contribute to the current realization of several advanced EMSs for the DN [43]–[46]. Today, the idea of EMS has become even more applicable at various demand-side systems, and it has been extended to be used at urban scale level [47], [48], office building level [49]–[54], and household level [51], [55]–[63]; these systems commonly aim to realize sophisticated control by using computational assist and collected data based on information communication [64]–[68]. Particularly, many recent works address the high PV penetration for residential consumers and the effective operation of energy devices, such as storage batteries, heating, ventilating, air-conditioning systems, fuel-cell cogeneration systems, EVs, and other home appliances through home energy management system (HEMS) to minimize the energy cost [50], [69]–[73]. These various levels of EMSs become essential components of the smart city [74].

While each EMS governs the optimization within a corresponding subsystem, a cooperative operation among multiple EMSs is the key to achieving the best performance for a whole city while fulfilling various requirements, such as maximizing the use of variable RESs, maintaining the frequency and voltage of the grid, minimizing energy cost, and ensuring resiliency. This point becomes more significant as the number of DER connected to the DN increases because the power flow becomes bidirectional, so that conventional methodologies become inadequate. Recent researches have focused on the operations for voltage regulators [75], [76] located in the DN based on the change in the power flow to alleviate voltage issues [77], [78]; these frameworks suggest that highly automated GEMS has a possibility to improve the hosting capacity of the PV [79], [80] and energy devices like EVs [81]. However, simple optimization among consumers, such as the reduction of residential electricity charge [71] and provision of comfort [82], [83] and convenience [84], may cause unexpected negative impact on the local voltage quality [78], [85] and excessive power loss in the grid [86], possibly leading to a reduction in the PV hosting capacity and/or an increase in CO_2 emission in the target area. Several recent works have focused on the influence of massive installation of demand-side EMSs from the viewpoint of district level [87] and have shown that some issues in the DN, e.g., voltage deviation, can be alleviated by massively installed sophisticated HEMSs [85], [88], [89] communicating with other EMSs. This trend also suggests that cooperation among EMSs, especially between a supply-side EMS, i.e., GEMS, and demand-side EMSs (e.g., HEMS for a residence or building energy management system (BEMS) for a building) is important and needs coordination at the city scale.

The proper evaluation of the effects of cooperation among multiple EMSs and development of appropriate algorithms to operate them in a coordinated manner are crucially important in the design of sustainable smart cities. In addition, the multiple EMS scheme involves another important aspect of how to utilize the collected data [90], such as the detailed electricity consumption information obtained at smart meters, voltage data representing the power quality of the local electric power grid [91], and meteorological information that is important for both energy-efficient urban planning [92] and spatiotemporal transition evaluation of installed PV generation systems [93], [94]. Simulation models have been developed specifically for the purpose of evaluating city-scale districts (see [95]–[99] for comprehensive surveys). For example, the simulation of various load patterns constituting a city has been discussed from the viewpoint of architecture, urban planning, and building energy systems [100]–[102]. In the context of dealing with city-scale power flow, evaluation schemes of demand-side energy systems composed of a set of building models [103] and the supply-side system composed of DN models [104] have been integrated for an analysis of spatiotemporal variations of zoned energy consumption patterns and optimization of the target area [87]; in this framework, the simultaneous control of demand/supply-side EMSs through multi-objective optimization is proposed with respect to the total annual cost, CO2 emission and primary energy consumption. There have been some other simulation-based studies for city level analysis of EMSs, e.g., architecture of decentralized energy systems [105], optimization of demand-side resources [106], and large-scale deployment of demand-side EMS realizing nearly zero-energy buildings (ZEBs) [107]–[109] on a model grid [110]. These previous works basically focus on the behavior of hourly power flow and do not incorporate the effect of changes in power flow in relatively short time.

As will be shown later in this paper, the evaluation of the sustainability of smart-energy infrastructure in a city owes much to voltage fluctuations and a margin for the transformer capacity in the DN affected by short-term power flow variations. Recently, Baetens *et al.* have developed a simulation tool called IDEAS (Integrated District Energy Assessment by Simulation) [111] for the evaluation of voltage, loss, and current overload in the DN with ZEBs. This tool, based on the IEEE radial distribution 34 Node Test Feeder [112], contains dozens of building models with demand-side energy systems at the low-voltage (LV) distribution system, and focuses on the power flow with a 1-min resolution. An assessment provided by IDEAS is important in evaluating the sustainability of the energy infrastructure at the city level. A recent report on smart grid projects in Europe [113] has also shown several ambitious challenges on the framework for home, building and district level end users to manage more effective energy use (e.g., CITyFiED project [114] and SINFONIA project [115]), so that a platform for modeling and evaluating city level cooperative EMSs becomes very important.

In this paper, we present a versatile spatiotemporal evaluation platform accommodating mutually cooperating EMSs for designing and analyzing smart cities to improve existing models and operation approaches.

III. EVALUATION SCHEME OF SMART-CITY ENERGY BY USING EMS PLATFORM

This section describes several requirements for evaluating EMS methods for a sustainable energy infrastructure in a city, and introduces a scheme of evaluation methodologies that have been considered for our platform.

In our modeling, we are focusing on the issues in DN and consumers associated with large penetration of DERs, and analyses based on the scenarios considering what kind of and how much resources are connected to the DN. Cooperative operation among EMSs (GEMS and BEMS/HEMS) will contribute to various DN level challenges such as voltage regulation and reduction of loss. Here, we placed some problems out of our scope. Each DN is connected to TN and DERs might be collectively controlled to support the supply-demand balance in the whole power system. In addition, the contribution from DERs are generally traded through markets and/or procured by the system operators as well as other business entities such as retailers and aggregators. In our scheme, we are not directly dealing with these system level and economic issues, but will include into the constraints given to the EMSs and the objective functions. On the other hand, toward the massive installation of DERs in DNs, it is desired to have the aggregated model of the DNs considering dynamic properties of DERs and loads, which is applicable to the whole power system analysis. This theme is under study in our separate work.

A. Evaluation Scheme

Energy management in a real-world electricity infrastructure is realized by communicating and processing various data types obtained from controlled devices, meteorological stations, and human behavior [116], [117], so that it is difficult to estimate the impact of a given EMS on a city. An EMS evaluation platform can be a powerful tool for simulating the physical perspective of the city to verify the effects of the implemented EMS technologies in a cyber world that connects numerous energy devices and subsystems organically through information processing [118]–[120]. From the viewpoint of evaluating the effectiveness for building a smart city, sustainability of solutions to universal issues that can occur in a city with the target scale characterized by target demand and weather tendency is critical. In this study, we consider the following procedure for evaluation:

1) **Selection of the target district**: considering land use, configuration of buildings, and demand types of the target district.
2) **Construction of an EMS platform**: constructing a simulation model to reflect practical information, including network structure, demand patterns, and meteorological observations.

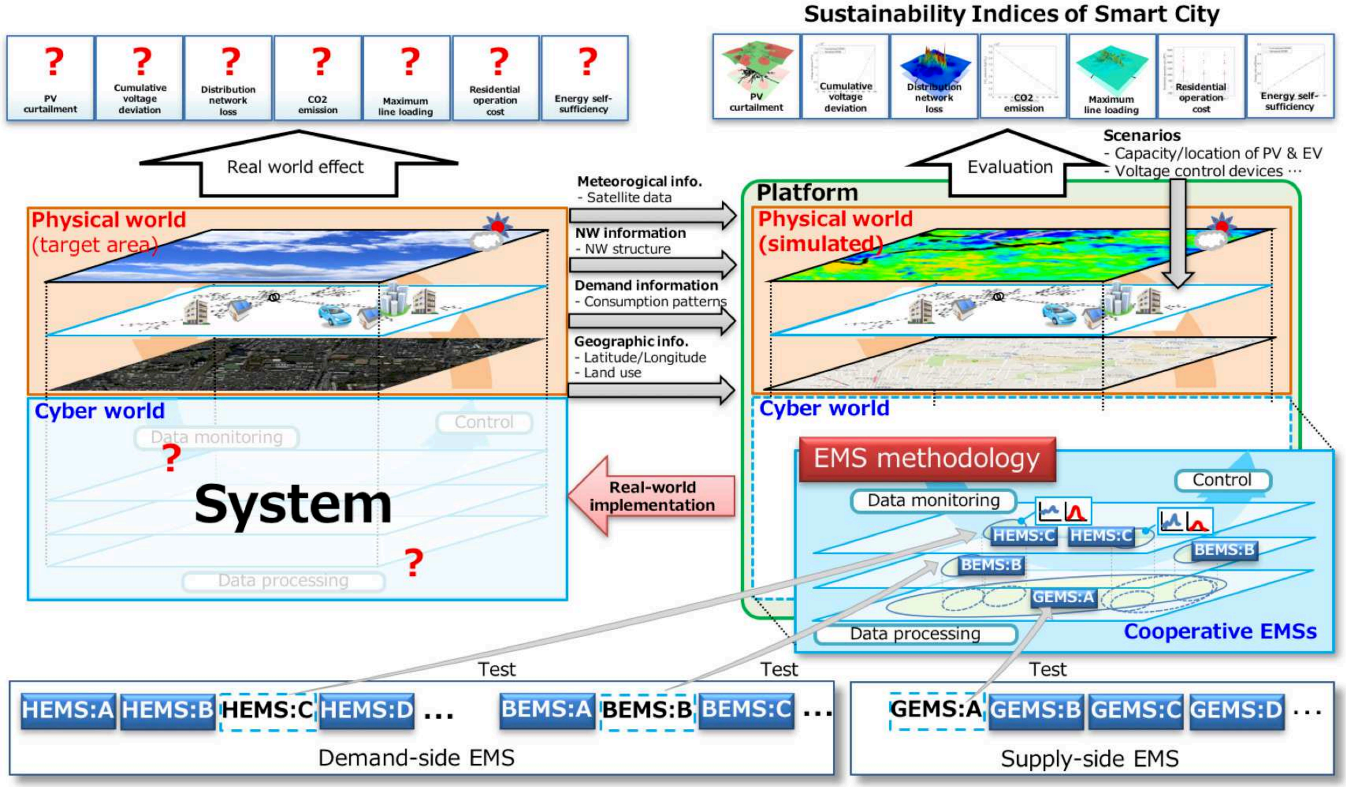

Fig. 1. Schematic image of a platform for cooperative EMSs in a smart city. The real target district (left) consists of *physical components* and *cyber components*. Energy management in the real district is realized by communicating and processing various data related to control objects, weather, human behavior, etc. The platform (right) plays the role of quantitatively evaluating the impact for the city from several perspectives by simulating the broader physical environment.

3) **Creation of evaluation scenarios**: allocating various demand-side energy appliances (PVs, EVs, and other energy appliances) and supply-side devices (SVRs, voltage sensors, and other control devices).
4) **Evaluation of the EMS methodology**: incorporate EMSs into the evaluation platform and determine appropriate metrics within the larger goal of sustainability in the smart city.

Fig. 1 shows a schematic overview of our EMS evaluation scheme for a smart city. The relevant physical components in the target cities are expressed as a digital model for a simulation on the EMS platform, then the EMS methodology, which is a set of EMS algorithms including data acquisition, processing and exchange, is incorporated. For example, there could be some supply-side EMSs (GEMSs in Fig. 1) which control tap positions of LTC and/or SVR to properly regulate the voltage in DN, and, in some scenarios, change the physical configuration of DN to improve electricity flow and minimize loss. The demand-side EMSs (HEMSs and BEMSs in Fig. 1) would change, e.g., electricity consumption according to PV generation forecast and/or demand response requirement. In most cases, we assume that the supply side EMSs are acquiring the active and reactive power flow data and/or the voltage data at some locations, e.g. the substations, SVRs and switches, while the demand-side EMSs monitor the electricity consumption of each device and PV generation. In addition, we may assume data acquisition and exchange among these EMSs through an appropriate communication network depending on the scenario being examined. Some examples of technical details of the cooperative control of multiple EMSs can be found in our previous works [121], [122] and other studies [116]–[120]. Thus, our platform provides a “ground” where we can test EMS algorithms. By utilizing such a platform, the quantitative effects of the developed EMS on the physical world can be evaluated from various viewpoints. In particular, we focused on the following indices (see Appendix for more details):

- PV curtailment
- Cumulative voltage deviation
- DN loss
- CO_2 emission
- Maximum line utilization
- Residential operation cost
- Energy self-sufficiency

These indices are suggested to be the minimum requirements for meaningful evaluation.

For the appropriate analysis of the EMS based on these sustainability indices, the evaluation platform particularly requires the following four modeling descriptions:

(i) electric power demand structure characterizing the target city,

(ii) detailed distribution system structure mapped on the target district,
(iii) spatiotemporal transition patterns of the demand, and
(iv) local meteorological dynamics of the target district.

Note that the treatment of these descriptions in the conventional simulation models introduced in Section II are insufficient for evaluation from the viewpoint of scale and spatiotemporal granularity. To satisfy these requirements, we (i) focus on the public statistics which characterize the demand structure of the target city, (ii) construct a plausible distribution network model corresponding to demand growth based on the network data provided by the utilities and mapped to the target district, (iii) associate consumers' demand patterns on the DN from the public database summarizing information from regional categories of the city to reproduce the precise spatiotemporal demand pattern, and (iv) introduce regional meteorological characteristics, e.g., solar radiation, based on data collected from a high-resolution meteorological satellite. A detailed distribution system model which includes both LV and medium-voltage (MV) nodes, is mapped onto the district. This model enables one to evaluate the behavior of the LV network system reflecting the behavior of consumers and grasp problems at the desired resolution corresponding to a *capillary vessel* of the electric power system. The constructed platform can clarify possible issues in the power infrastructure in the target district and evaluate the effects of cooperative operation among introduced EMSs from the viewpoint of sustainability indices. In addition, when the issues in the local energy supply/demand in the city are clarified, this framework realizes a flexible analysis of the cause and remedy by focusing on spatial and temporal power flow in the city.

B. Model Implementation

Implementation of the EMS platform on a target district can be achieved by utilizing various data of physical components related to the real-world electrical energy system. Table I shows examples of data sets which meet the requirements of the model introduced in the previous subsection aiming to evaluate the sustainability indices for the smart city. Since these types of data are obtained from different sources, we need a strategic implementation procedure to integrate the data sets into a consistent whole-energy system model. The remainder of this section describes the implementation process utilizing these data sets.

As a first step, we categorize buildings into four sectors, that is, (*residential*, *industrial*, *public*, and *commercial*), and three scales, that is, (*low-rise*, *medium-rise*, and *high-rise*), and calculate the ratio of total floor area for each building category from the land use data set to represent the demand structure.

The second step, which is the most challenging for reflecting the demand structure, is to create a unit energy system that can describe an entire city. This step is required to generate a plausible model out of all the available data, which is imperfect. A more precise procedure could start from the microscopic data of the elements, but such data set does not exist. In this study, we have several sets of data corresponding to actual distribution feeders, including both MV and LV systems with the connection points of MV loads and pole transformers, the net load, contract power of MV customers, and the length. However, the detailed demand information to connect those to building use and net floor area is not available, nor is the open feeder data set [128], [129]. In addition, there is no information regarding the LV other than the connection points to MV, although, as mentioned in the previous subsection, modeling the LV networks is important to grasp local electrical problems and evaluate the performance of demand-side EMS functionalities. To address these difficulties, we represent a collection of physical components. Initially, possible demand profiles are prepared at each connection point to the feeder, which is an MV demand and a pole transformer (an LV network). For the MV demand, the demand pattern candidates of various building uses are selected according to the contract power. Regarding the LV network, under the assumption that the building use is residential, several candidate LV networks are determined for each feeder to minimize the error from the given demand of the feeder. Since MV demand data are associated with customer information, such as the usage of the building and floor area, we can provide some additional information in addition to the demand patterns.

In the third step, by combining the candidates of the feeder-unit model, we construct the entire energy system model of the target district. To form the whole electrical network, characteristics of the demand structure and the network topology are considered. Regarding the demand, we determine a combination of electrical feeders that minimize the error of the building-type ratios between the target district and the feeder combinations. For the network topology, we connected the selected electrical feeders by assuming that the system has a typical DN structure. Specifically, a typical distribution substation consists of three banks, each of which connects with six feeders. These feeders are connected to each other via sectionalizing switches. From the network structure, we spatially place the selected feeders relative to the transformer banks. We then connect the feeders via the switches while avoiding distribution-line crossings. The representation of the entire network structure enables us to analyze the performance of the switch configuration (on/off states of switches) and distribution system restoration when a fault occurs.

We map this energy system model to the target district for analysis on local meteorological dynamics in the targeting DN. This geographical information is used for simulation of PV power output dynamics under the given evaluation scenario of PV allocations and sizes by using the solar irradiance data (see Table I). Firstly, node coordinates are determined by considering the length of the distribution line. Based on the determined node coordinates, the energy system model is then mapped to a given location on the target district. Naively, the objective function of node coordinates can be considered as an error of the distance between two nodes to the actual length of the corresponding distribution line. Still, this consideration alone leads to numerous possible node positions. To represent the network characteristics and reduce the freedom to place the node positions, we focus on a tree-structure (i.e., radial) network in which distribution lines expand from the substation. Specifically, we exploit a graph-layout algorithm proposed

TABLE I
DATA FOR IMPLEMENTING THE EMS PLATFORM

Category		Description
(i)	Land use	Land use data of Tokyo include a category of building use and total floor area of each building [123].
(ii)	MV electrical network	126 DNs at the MV level are sampled in management areas of TEPCO Power Grid, Inc., Chubu Electric Power Co., Inc., and Kansai Electric Power Co., Inc. in Japan. This data set has topology and power measurement information; the topology information includes distribution lines (line types and length), voltage transformers (capacities and impedance), switch locations, and customer contract powers. The power measurement includes active and reactive power recorded at a substation with a time step of 30[min].
	LV electrical network	415 DNs at the LV level are modeled with reference to real electrical networks in Tokyo, Japan. This model has topology information and network connection points of the customers.
(iii)	Electrical demand profile (a residential house)	Demand profiles of 553 residential houses were recorded in Ohta city, Gunma, Japan in 2007 [124]. The time step was 10[s].
	Electrical demand profile (a multi-family building)	Demand profiles of 333 households living in a multi-family building located in Settsu city, Osaka, Japan was recorded. The time step was 1[min]. This data set is available from [125]
	Electrical demand profile (industry and business sectors)	Demand profiles of 5,727 industry and business buildings are recorded. The time step is 1[h]. This data set has 15 categories of building use (supermarkets, drug stores, appliance shops, convenience stores, suburban shopping centers, other types of shops, restaurants, banks, offices, medical buildings, administrative, meeting places, educational buildings, hotels, and factories). This data set is available from [126].
(iv)	Solar irradiance	Global, diffuse, and direct horizontal irradiances were estimated from geostationary satellites of Himawari-8 with a resolution of 1[km] mesh [93]. The time step was 2.5[min]. This data set is available from [127].

by Gansner *et al.* [130] for mapping the targeting DN to the district of interest. The algorithm determines the node coordinates according to the following energy function:

$$E = \sum_m \sum_n W_{mn} (\|p_m - p_n\| - l_{mn})^2, \tag{1}$$

where p_m and p_n are the coordinates of nodes m and n, respectively, l_{mn} is the shortest path distance of nodes m and n, and W_{mn} is the weighting coefficient according to l_{mn}. Since this function evaluates the shortest-path distances of all pairs of nodes, the minimizer finds that farther nodes in the DN are located relatively farther in the physical space. In other words, we can expect to obtain the nodes expanding from a substation. After applying this graph-layout algorithm, we map the node coordinates to a given location on the target district.

TABLE II
MODEL USED IN THE TUTORIAL

Target city	Latitude	$35°38'36.39''$ N
	Longitude	$139°35'00.19''$ E
	Area	4.8×5.5 [km]
	# households in LV	$10,549$
	# consumers in MV	186
DN model	# feeders	18
	# OLTCs	3
	# switches	140
	Load capacity	2,971 [kVA]
	Acceptable LV range	95 - 107 [V]
Spec of PV inverters	Curtailment starting voltage	107 [V]
	Curtailment ending voltage	106.5 [V]
	Speed of curtailment	0.002 [kW/s]
Spec of EVs	Rated output for charge / discharge	3.0 / 4.0 [kW]
	Capacity	30 [kWh]
Driving schedule	Driving time	7:00-7:10, 7:20-7:30, 18:30-18:40, 18:50-19:00
	Parking outside	7:10-7:20, 18:40-18:50
	Parking at house	otherwise
TOU pricing	00:00-7:00	9.33 [JPY/kWh]
	07:00-09:00	21.23 [JPY/kWh]
	09:00-17:00	31.43 [JPY/kWh]
	17:00-24:00	21.23 [JPY/kWh]
Feed-in-Tariff		30.00 [JPY/kWh]

IV. EVALUATION OF THE EMS FOR A SMART CITY

In this section, two examples of sustainability evaluation of the electricity infrastructure for a target district based on the proposed EMS platform are detailed. The first example focuses on upcoming problems in the DN within a target city caused by the introduction of residential PVs [131], [132]; an advanced supply-side EMS is introduced to address these problems, and the potential to improve the PV hosting capacity and energy self-sufficiency of the city is evaluated. In the second example, the wide-scale introduction of EVs [121], [122], [133] in the city is evaluated; demand-side EMSs and information sharing among several systems critically change the city energy flow, so that the proposed platform reveals arising performance problems and possible solutions to increase the EV hosting capacity.

A. Description of the EMS platform

In our case studies, we focus on a virtual but plausible distribution network in a target district (Komae city, Tokyo, Japan) constructed based on the procedure given in the previous section.[1] We show the electricity consumption ratio of the target district in Fig. 2(a) with a plausible distribution network topology mapped onto the target district; Fig. 3 shows the city model implemented on the EMS platform drawn on Google Earth. We emphasize that the transition of the PV outputs generated at various points on the DN are simulated based on solar radiation information [93] provided by a Japanese weather satellite, i.e., Himawari 8 [134]; the solar radiation information has spatial resolution of 1 km and was collected

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[1] This paper has supplementary downloadable material available at http://www.waseda.jp/across/en/news/2554/ provided by the authors.

every 2.5 min for the target district. The description of the model used in this study and an example of the daily total electricity consumption profile are given in Table II and Fig. 2(b), respectively. Fig. 3 shows a snapshot of our model mapped onto the target district[2].

B. Evaluation of PV hosting capacity

In the first case study, the effects of PV penetration in a city are evaluated. A proportion of households is randomly extracted from 10,549 samples connected to the LV network and equipped with the residential PV systems specified in Table II. Note that the model city constructed on our platform reflects real-world household density, and that the PV introduction simulated here is spatially non-uniform.

Fig. 4(a) shows the relationship between the residential PV penetration rate and the DN loss in the city. Dispersed introduction of residential PVs drastically changes the power flow in the DN and improves the local balance of generation and consumption, so that the DN loss steadily improves before declining above some PV total capacity. If the amount of dispersed PV exceeds this capacity boundary, reverse power flow increases the current, leading to a slight increase in DN loss. Fig. 4(b) also shows the total CO_2 emission due to electricity consumption in the city; the CO_2 emission is drastically improved by the reduction of fossil fuel power generation corresponding to the total PV introduction and DN loss improvement.

We compare two voltage control schemes for the operation of the DN; although various voltage control schemes can be implemented in our platform, we selected these schemes to clarify the difference of voltage control effectiveness and support to recognize how to apply our platform. The first is a voltage control scheme called *program control*, which is one of the popular methods adopted in the current Japanese electric power system provided by conventional GEMS. The voltage in the DN is controlled by on-load tap changers (OLTCs) and step voltage regulators (SVRs) according to well-tuned tap position schedules [135], [136]. The second is a centralized voltage-control scheme [132], [137] provided by advanced GEMS. In this scheme, voltage in the DN is dynamically controlled by OLTCs and SVRs according to the real-time data collected by using a supervisory control and data acquisition (SCADA) system. We assume that the SCADA system acquires the real-time voltage data at all LV nodes. The OLTCs and SVRs adjust their tap positions according to the acquired voltage data to maintain voltage in their control area within an acceptable range.

Fig. 5 shows a comparison of the GEMSs under various residential PV penetration rates from the viewpoints of PV curtailment, cumulative voltage violation, and energy self-sufficiency. The node voltage under the conventional GEMS tends to deviate excessively when the PV penetration rate is high, so that the installed PV output tends to be suppressed by the PV inverter; however, these problems are drastically reduced by the advanced GEMS. Fig. 5(c) shows the phenomena from the viewpoint of an energy self-sufficiency index for the city. The energy self-sufficiency improves linearly according to the PV penetration in our setup, but the improvement effect is weakened due to suppression of PV output under the conventional GEMS. These results suggest that the city-level PV utilization can be improved and the advanced GEMS framework can contribute to designing sustainable smart cities.

Fig. 6 shows typical curves of the total PV output and the electricity load in the city. Fig. 7(a) shows a snapshot of the losses in the DN with no PV; a large loss arises near the substation due to the power supply to remote terminal nodes. Fig. 7(b) also shows the same plot under a large amount of PV installation (80%) during the same time-slice. The dispersed PV introduction drastically changes power flow in the DN, so that the local balance of generation and consumption is improved and decreases loss. In addition, Fig. 8 shows the snapshots of the voltage distribution in the DN under the high PV installation rate (80%). Fig. 8(a) indicates that the voltage is too high with the conventional GEMS; thus, the generated PV tends to be curtailed at several terminal nodes. However, the voltage can be controlled within an acceptable range under the advanced GEMS, as shown in Fig. 8(b).

The results described here clearly show that the implementation of an advanced GEMS improves power flow in the DN, so that the sustainability indices improve while keeping the voltage within the desired range, and that PV hosting capacity can be increased.

C. Evaluation of EV penetration effects

The second case study simulates the impacts of EV penetration under large PV installation (80%) by using the advanced GEMS described in the previous section. Here, we assumed that a certain proportion of households extracted randomly introduces and utilizes EVs in daily life for daily nearby activities, such as shopping.

We compare penetration scenarios of the following three types of EVs from the demand-side perspective for households scattered throughout the city and the supply-side perspective for the DN, and then highlight how the cooperative information exchange between GEMS and HEMSs effectively improve multiple indices..

1) *Stand-alone EV*: the battery is charged as soon as the vehicle arrives home from the last driving in a day.
2) *EV controlled by HEMS*: the battery is charged and discharged according to the schedule provided by the HEMS to reduce the residential operation cost.
3) *EV controlled by cooperating EMSs*: the battery is charged and discharged according to the schedule that the HEMS derives through information exchange with the GEMS [121], [122] to reduce the residential operation cost while balancing the temporal load on the DN. The HEMSs send their EV charge-discharge schedules to the GEMS. The GEMS classifies the EVs into some groups and shifts the charging periods of each group to mitigate the negative impact of simultaneous charging on the

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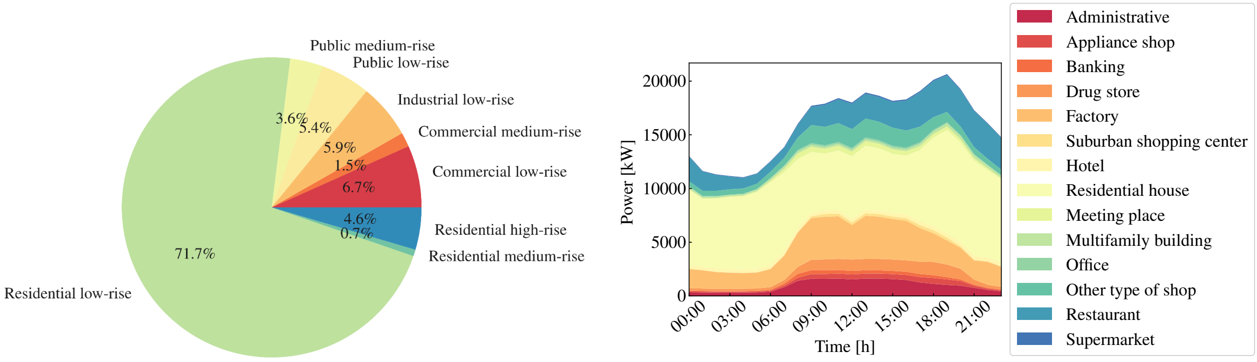
[2] This paper has supplementary downloadable material, which will be available at http://ieeexplore.ieee.org, provided by the authors. This includes the four multimedia files composed of MOV format movie clips. This material is 95.8 MB in size.



(a) Ratio of electricity consumption types.

(b) Illustration of the electricity consumption profile.

Fig. 2. Electricity consumptions of the model city; (a) the ratio of electricity consumption types, and (b) illustration of the daily electricity consumption profile.

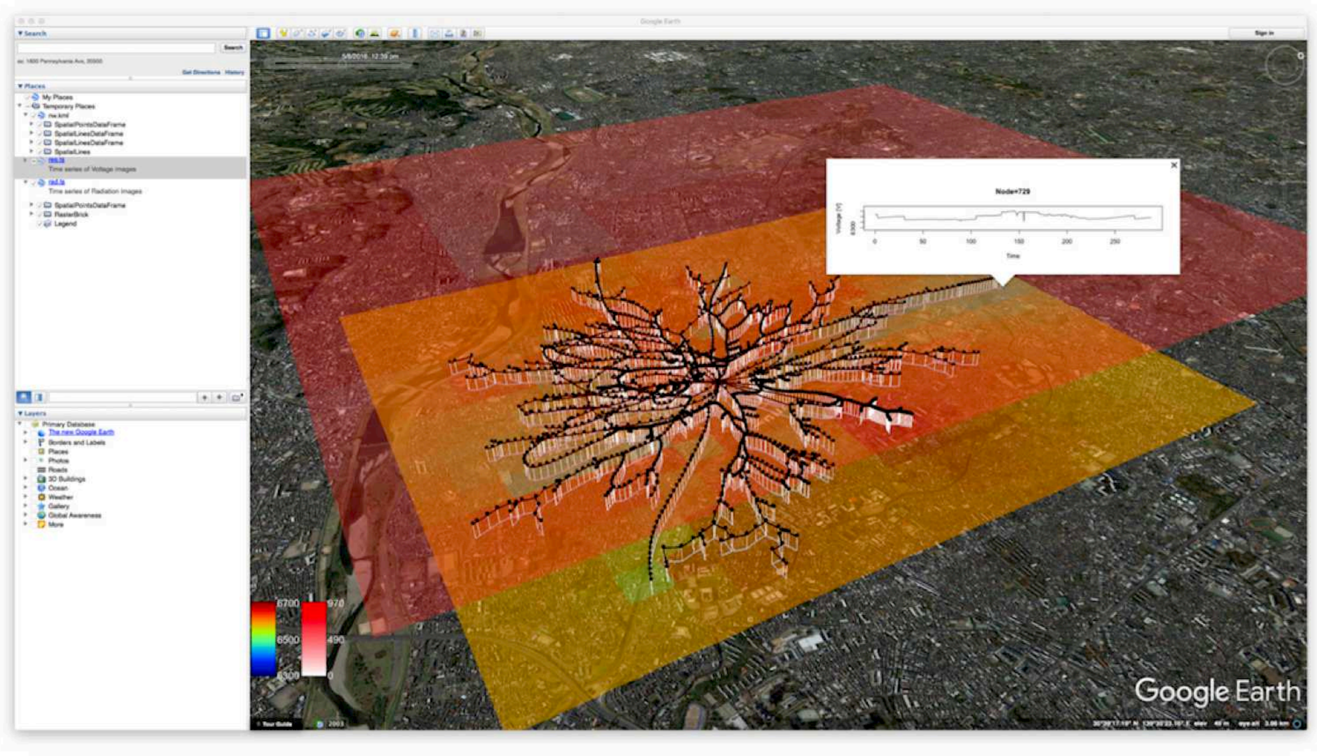
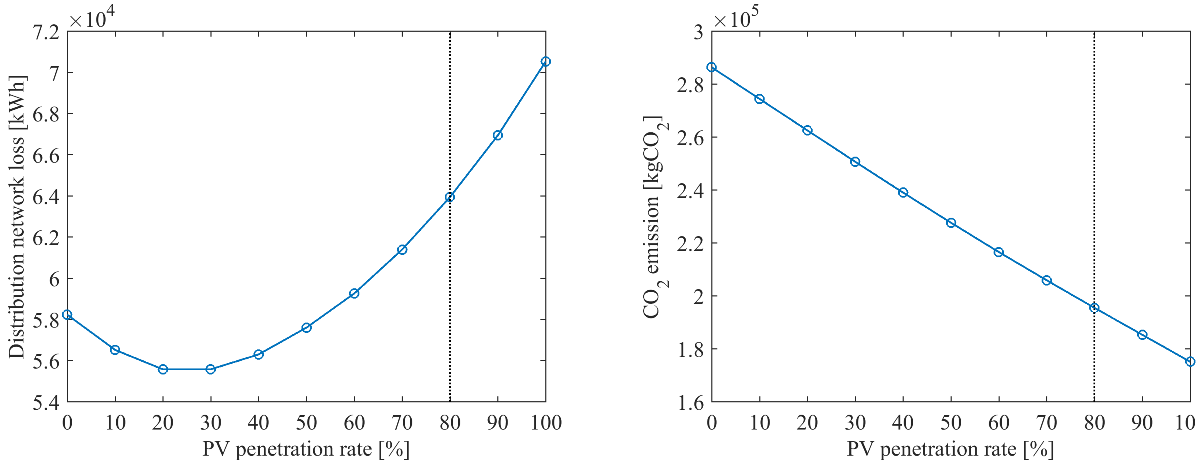
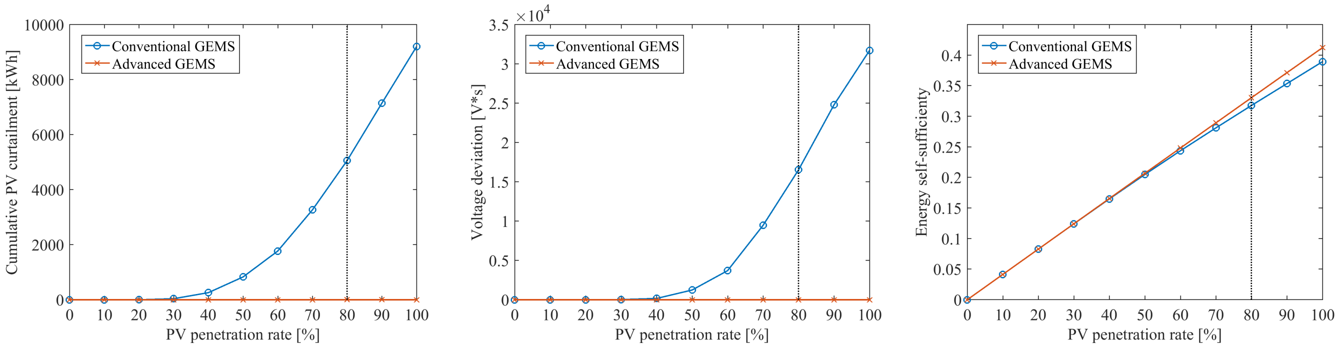


Fig. 3. Snapshot of the constructed EMS platform used in our evaluation. The DN model is mapped onto the target district, and various consumers are allocated on the nodes by reflecting characteristics of the target city. Spatiotemporal information collected in the physical world is provided to the simulated physical system. In this figure, solar radiation data collected through a meteorological satellite is shown in the upper plane. By allocating demand-side energy appliances (PVs, EVs, and other energy appliances) and various supply-side devices (SVRs, voltage sensors, and other control devices), the spatiotemporal dynamics of power quality in the city is derived. In this figure, voltage information reflecting reverse power flow from the distributed residential PVs corresponding to the current solar radiation is shown in the lower plane. Temporal transition of spatial information is visualized by operating the slide bar in the graphical user interface and the time series behavior at each point can be visualized as a graph. We have included a supplementary MOV file recording EMS platform visualized by using Google Earth. This is available at http://ieeexplore.ieee.org.



(a) DN loss (b) CO_2 emission

Fig. 4. Relationships between the residential PV penetration rate and (a) the amount of DN loss, and (b) the amount of CO_2 emission in a city



(a) PV curtailment (b) Cumulative voltage violation (c) Energy self-sufficiency

Fig. 5. Comparison of GEMS under the various residential PV penetration rates from the viewpoint of (a) PV curtailment, (b) cumulative voltage violation, and (c) energy self-sufficiency.

grid. Then the HEMSs modify their EV charge-discharge schedules considering the charging periods requested by the GEMS.

In the case of type-2 EV, the battery is charged by preferentially utilizing the residential PV output in each house which might be suppressed (if the target house has PV), and also charged when the electricity rate is relatively low according to the given TOU (Time-Of-Use). The schedule adopted in type-3 EVs is basically the same as that in type-2, but avoids the simultaneous charging of a large number of vehicles, so that the individual batteries are charged at various timings during the low-price period.

Fig. 9 shows the relationships between the EV penetration rate and the cumulative voltage violation in the DN, maximum line-utilization rate, and energy self-sufficiency of the city. The results shown in Fig. 9(a) imply that the penetration of type-1 EV has a relatively large impact on the DN voltage, since most of the vehicles are likely to be charged during the heavy load period after returning home. The penetration of type-2 EVs alleviates much of the problem, though the voltage deviation by EV charging at the low-price period can be still an issue. In contrast, the penetration of type-3 EVs can alleviate the voltage issue drastically by cooperation among the HEMS and GEMS. Fig. 9(b) shows the maximum line-utilization rate. A utilization rate above 1.00 indicates the line-capacity constraint violation of the DN. This can be an important index for the estimation of EV hosting capacity in the city. The result shows that penetration of type-1 EVs has a severe impact on this index since a heavy load cannot be alleviated by the voltage control provided by the advanced GEMS; in this case, a change in battery-charge timing based on the network status is effective, so that type-3 EVs are expected to be a better scheme for such high levels. Fig. 10 shows a boxplot of the residential operation cost of the EV owners when the EV penetration rate is 60%. The result indicates that the residential operation cost can be improved by the introduction of the HEMS (type-1 → type-2), and does not become worse by cooperation of EMSs (type-2 → type-3).

Fig. 11 shows a typical daily sequence of the total charge/discharge of EVs in the city under an EV penetration rate of 60%. Fig. 12 shows the corresponding snapshots of the voltage distribution in the DN. Type-1 EVs may cause drastic voltage drops in the evening due to simultaneous charging as shown in Fig. 12 (c). In contrast, the type-2 EVs can alleviate the voltage drop in the evening (Fig. 12(f)); however, it causes a significant voltage drop around midnight. Contrary to these cases, no noticeable voltage problems arise during any time-slice for the type-3 EV. Fig. 13 shows the snapshots of line-utilization rate distribution. Fig. 13(c) reveals the

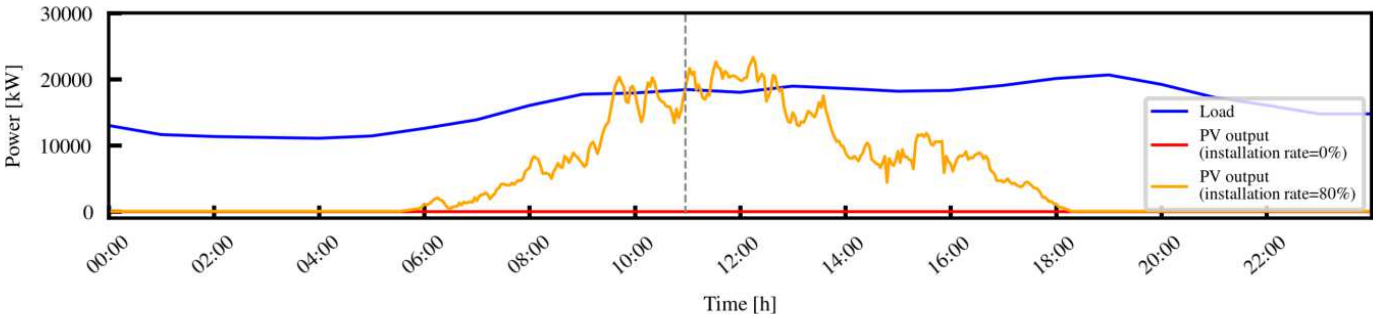
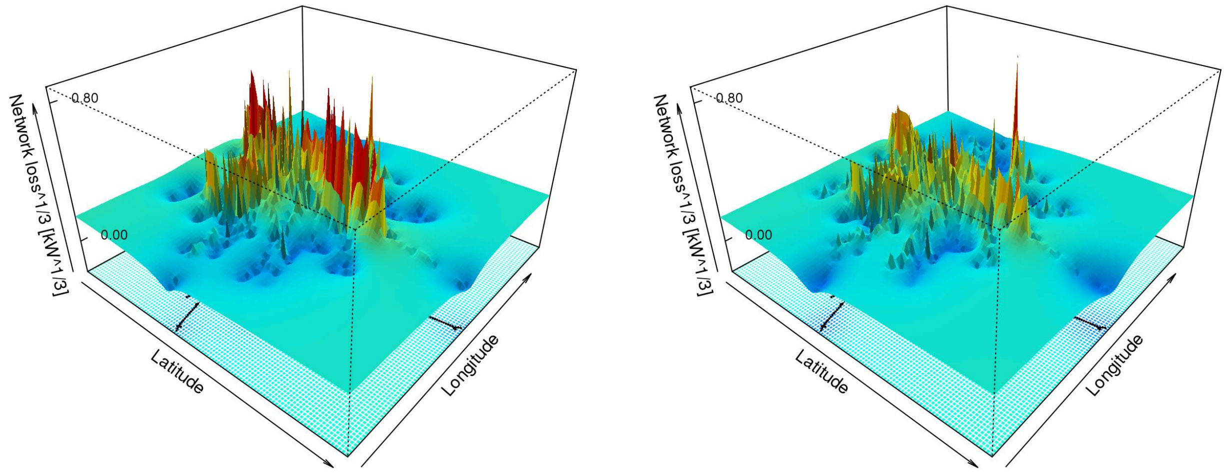


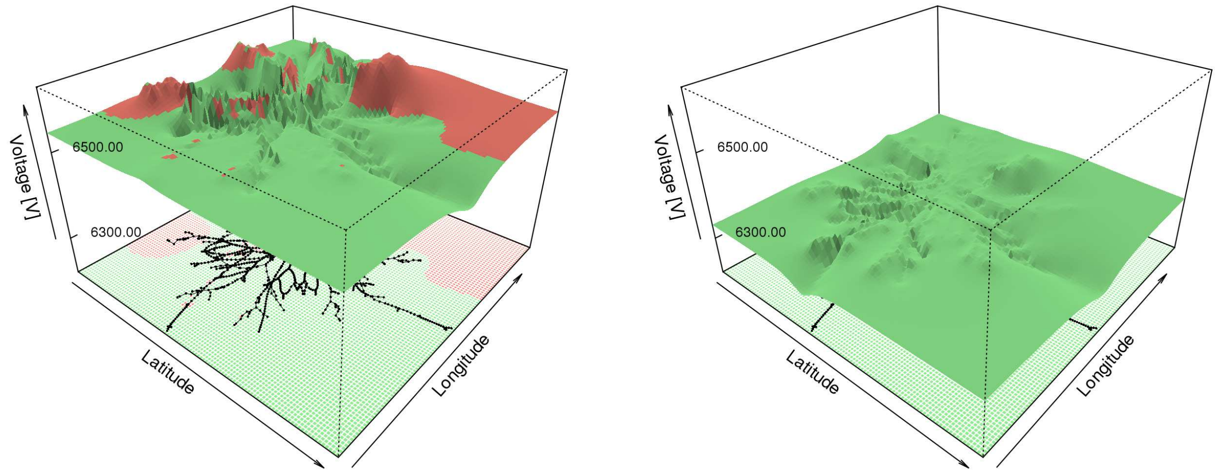
Fig. 6. Curves of the total PV output and load in the city. The time-slice at 11:00 is expanded in Figs. 7 and 8.



(a) PV installation rate = 0%

(b) PV installation rate = 80%

Fig. 7. Snapshots of the loss distribution on the DN in the city with (a) no PV and (b) an installation rate of 80%. High-loss subareas are shown in red. The figures focus on the same time-slice (at 11:00).



(a) Conventional GEMS

(b) Advanced GEMS

Fig. 8. Snapshots of the voltage distribution on the distribution network in the city under (a) the conventional GEMS and (b) the advanced GEMS. PV curtailed subareas are shown in red; otherwise, subareas are shown in green. The figures focus on the same time-slice (at 11:00).

existence of overload in the evening for type-1 EV penetration. Though type-2 EVs can alleviate the overload in the evening (Fig. 13(f)), it may lead to an overload period around midnight (Fig. 13(d)). Type-3 EVs cause no line-utilization problem as shown in Figs. 13(g)–(i). Note that such an overload problem cannot be avoided solely by advanced voltage control schemes provided by GEMS, but can be alleviated by shifting the consumers' electricity through cooperation between GEMS and demand-side EMSs.

These results show the role and effect of the cooperative operation of the supply-side and demand-side EMSs, and suggest a possible framework for the improvement of EV hosting capacity in the city. Our platform provides a powerful tool for the assessment of specific policies, e.g., incentivizing EV by regulatory sectors and electricity price strategy by utilities.

V. CONCLUDING REMARKS

In this study, we have described a highly versatile platform to design and evaluate smart cities that consists of models for distribution networks and consumers set interacting through EMSs in the physical world as well as data acquisition and analysis functionality in cyber space. We have presented the architecture of the developed platform and shown two case studies with the extensive deployment of PV and EV using visualization. We emphasize that our platform is widely applicable to energy issues in different cities, including industrial, commercial, and residential districts. Once the city model is created, the hosting capacity of PV and EV as well as other DERs can be displayed to reveal a spatiotemporal profile of voltage, energy loss, and other performance parameters. In addition, the platform can be used to evaluate the impact of a specific policy, e.g., incentivizing PV installation in targeted areas, introducing TOU pricing, implementation of demand response, construction of EV charging stations, etc. For the Tokyo Olympic Games to be held in 2020, the construction of a smart city will be promoted through several national demonstration projects supported by the Japanese government. Our platform can be used to evaluate these plans and extended into transportation concerns.

ACKNOWLEDGEMENTS

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APPENDIX

The indices used in our evaluation are defined as follows. Note that we focus on the effective values of voltage and current in these indices for evaluation of steady state power systems.

Definition 1 (PV curtailment)**.** *Let $h \in \mathcal{H}$ be the index of the household connected at LV nodes and $t \in \mathcal{T}$ be the index of time-slice in the evaluation period. Then, the PV curtailment at LV nodes is defined as*

$$\sum_{t \in \mathcal{T}} \sum_{h \in \mathcal{H}} s_t^h,$$

where s_t^h is the suppressed PV output at time-slice t in household h. ☐

Definition 2 (Cumulative voltage deviation)**.** *Let $n \in \mathcal{N}$ be the node index on the DN and $\delta(a)$ be the hinge function, i.e.,*

$$\delta(a) = \begin{cases} a & (a \geq 0) \\ 0 & (a < 0). \end{cases}$$

Then, the cumulative voltage deviation is defined as

$$\sum_{t \in \mathcal{T}} \sum_{n \in \mathcal{N}} \{\delta(V_t^n - V_{\text{upper}}^n) + \delta(V_{\text{lower}}^n - V_t^n)\},$$

where V_t^n indicates the voltage at time-slice t on node n, and V_{upper}^n and V_{lower}^n indicate the upper and lower limits of the voltage at n, respectively. ☐

Definition 3 (DN loss)**.** *Let $(m,n) \in \mathcal{B}$ be the index of a linked node pair m and n on the DN. Then, the DN loss is defined as*

$$\sum_{t \in \mathcal{T}} \sum_{(m,n) \in \mathcal{B}} R^{mn} I_t^{mn2},$$

where R^{mn} indicates the resistance of the line between nodes m and n, and I_t^{mn} denotes the current at time-slice t. ☐

Definition 4 (CO_2 emission)**.** *Let $j \in \mathcal{J}$ be the index of consumers connected at the MV nodes; assume that $\mathcal{J} \cup \mathcal{H}$ indicates all the power consumers in the city. Then, CO_2 emission is defined as*

$$\alpha \sum_{t \in \mathcal{T}} \left\{ \underbrace{\delta\left(\sum_{h \in \mathcal{H}} (d_t^h - e_t^h) + \sum_{j \in \mathcal{J}} (d_t^j - e_t^j) \right)}_{\text{total net load}} + \underbrace{\sum_{(m,n) \in \mathcal{B}} R^{mn} I_t^{mn2}}_{\text{network loss}} \right\},$$

where α is a conversion coefficient determined by the ratio of power generation resource types, e_t^h is the generated PV output, and d_t^h is the electricity demand. ☐

Definition 5 (Maximum line utilization)**.** *Maximum line utilization rate of a DN in the evaluation period is defined as*

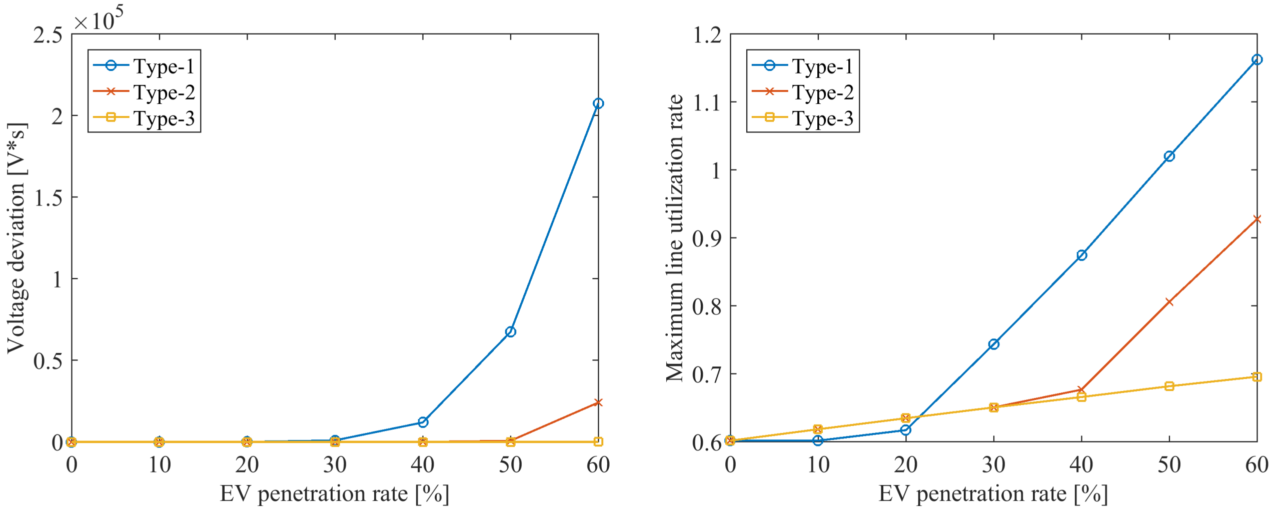
$$\max_{(m,n) \in \mathcal{B}} \frac{\max_{t \in \mathcal{T}} I_t^{mn}}{I_{\max}^{mn}},$$

where I_t^{mn} is the current of the line between nodes m and n at time-slice t, and $I_{\max}^{mn}$ is line capacity. ☐

Definition 6 (Residential operation cost)**.** *Residential operation cost for a household $h \in \mathcal{H}$ is defined as*

$$\sum_{t \in \mathcal{T}} \left\{ \beta_t \underbrace{\delta(d_t^h - e_t^h)}_{\text{purchased electricity}} - \gamma \underbrace{\delta(e_t^h - d_t^h)}_{\text{sold electricity}} \right\},$$

where β_t and γ are the cost conversion coefficients determined by time-of-use (TOU) pricing menu and FIT, respectively. ☐



(a) Cumulative voltage deviation

(b) Maximum line-utilization rate

Fig. 9. Relationships between the EV penetration rate and (a) the cumulative voltage violation, and (b) the maximum line-utilization rate.

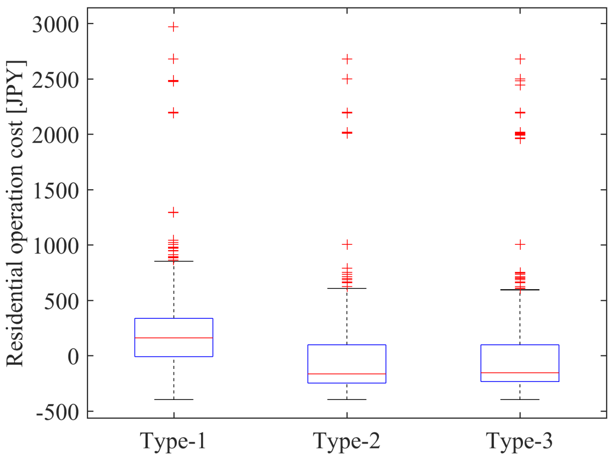


Fig. 10. Comparison of the residential operation costs of EV owners. Negative cost values indicate profits

Definition 7 (Energy self-sufficiency)**.** *Energy self-sufficiency rate of the city is defined as*

$$\frac{\sum_{t\in\mathcal{T}}\left\{\overbrace{\sum_{h\in\mathcal{H}} e_t^h + \sum_{j\in\mathcal{J}} e_t^j}^{\textit{total generation}}\right\}}{\sum_{t\in\mathcal{T}}\left\{\underbrace{\sum_{h\in\mathcal{H}} d_t^h + \sum_{j\in\mathcal{J}} d_t^j}_{\textit{total consumption}} + \underbrace{\sum_{(m,n)\in\mathcal{B}} R^{mn} {I_t^{mn}}^2}_{\textit{network loss}}\right\}}.$$

□

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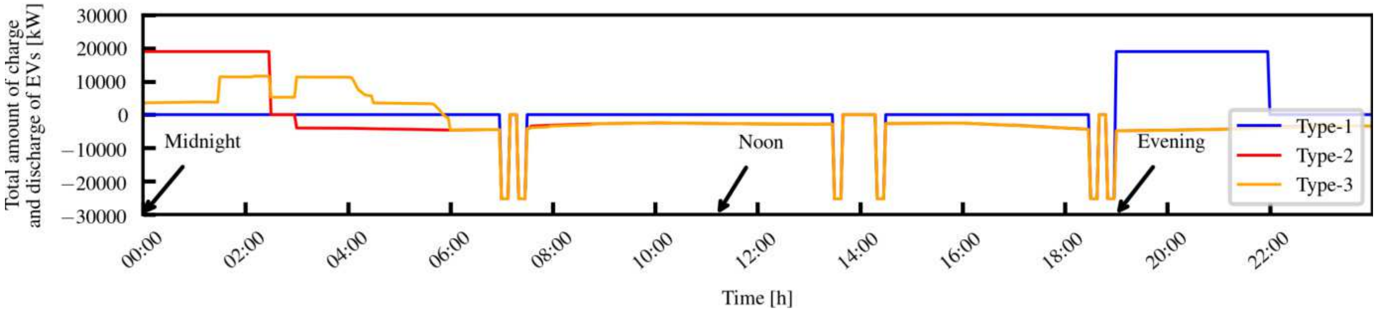
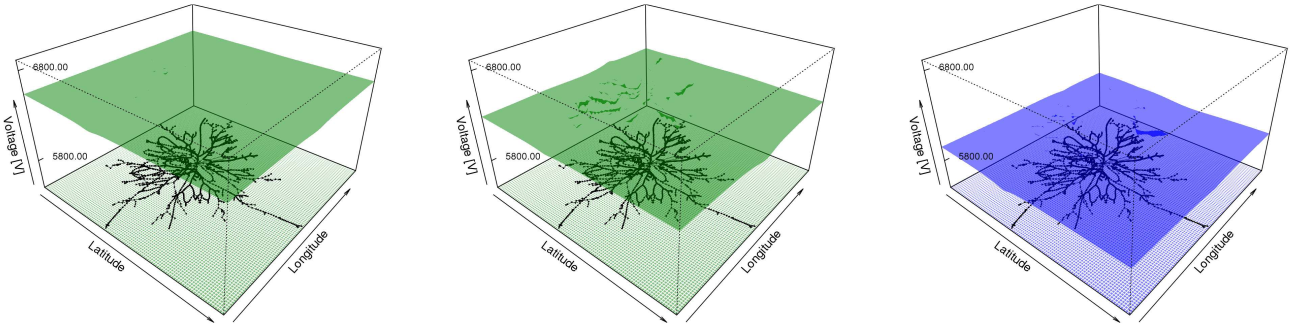
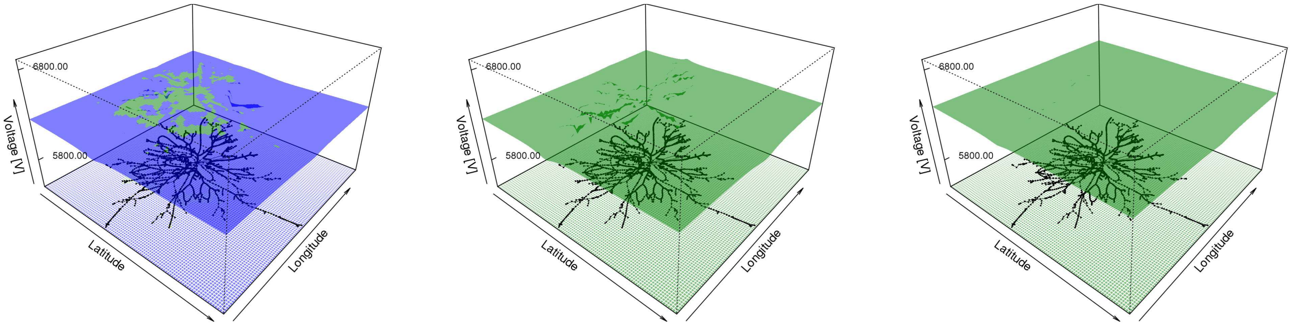


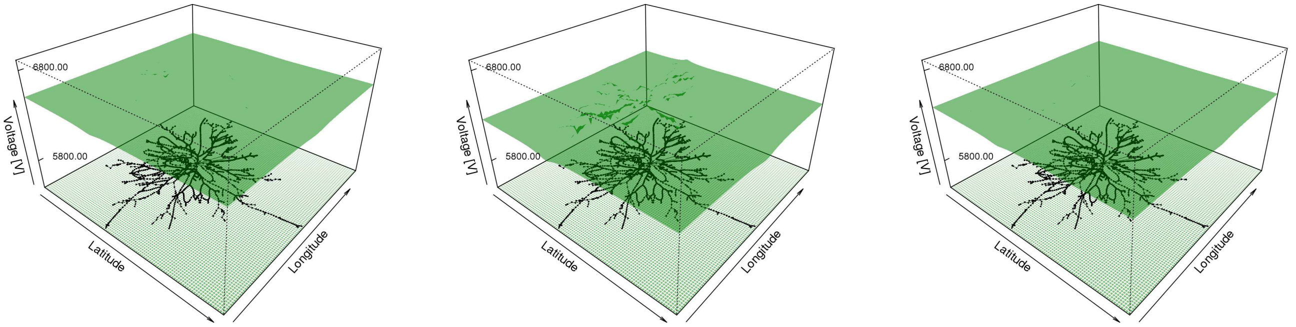
Fig. 11. Total amount of charge and discharge of EVs in the city.



(a) Type-1 EV (midnight) (b) Type-1 EV (noon) (c) Type-1 EV (evening)

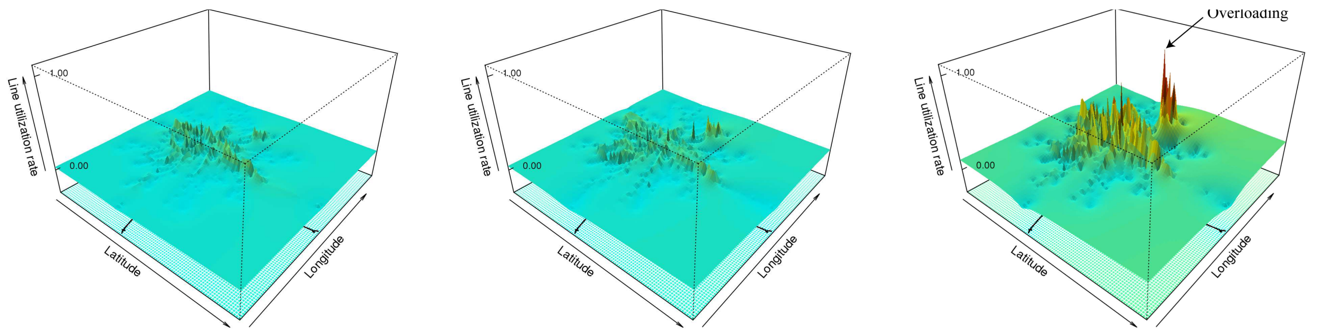


(d) Type-2 EV (midnight) (e) Type-2 EV (noon) (f) Type-2 EV (evening)

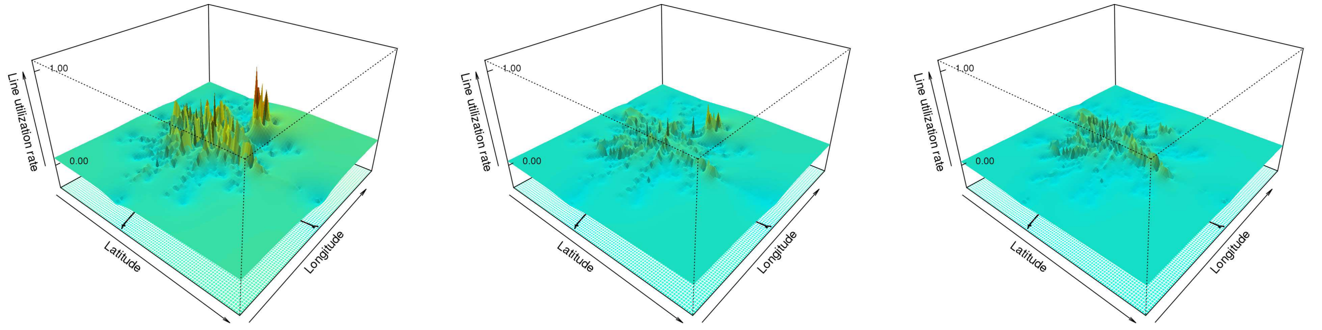


(g) Type-3 EV (midnight) (h) Type-3 EV (noon) (i) Type-3 EV (evening)

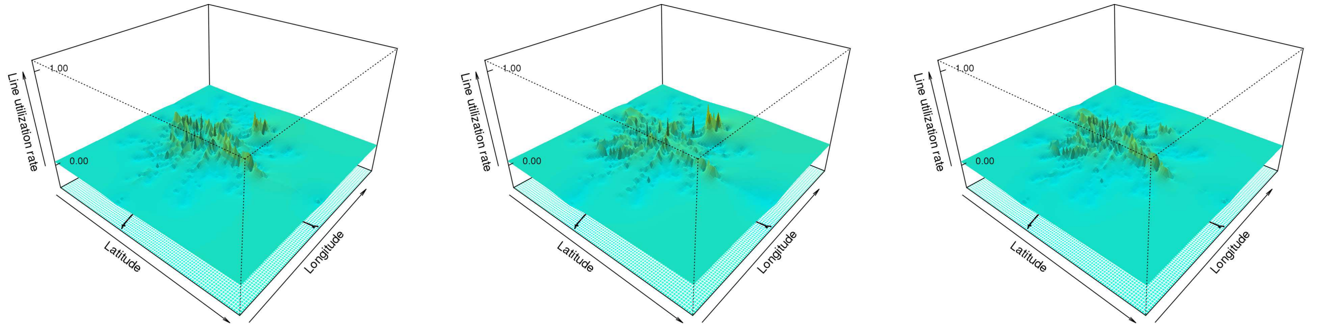
Fig. 12. Snapshots of the voltage distribution under a PV penetration of 80% and EV penetration of 60%; under the penetration of (a)–(c) type-1 EVs (stand-alone EVs), (d)–(f) type-2 EVs (EVs controlled by HEMS), and (g)–(i) type-3 EVs (EVs controlled by cooperating EMSs). Voltage deviated subareas are shown in blue, and the remaining subareas are shown in green.



(a) Type-1 EV (midnight) (b) Type-1 EV (noon) (c) Type-1 EV (evening)



(d) Type-2 EV (midnight) (e) Type-2 EV (noon) (f) Type-2 EV (evening)



(g) Type-3 EV (midnight) (h) Type-3 EV (noon) (i) Type-3 EV (evening)

Fig. 13. Snapshots of the line-utilization rate distribution under a PV penetration of 80% and EV penetration of 60%; under the penetration of (a)–(c) type-1 EVs (stand-alone EVs), (d)–(f) type-2 EVs (EVs controlled by HEMS), and (g)–(i) type-3 EVs (EVs controlled by cooperating EMSs).

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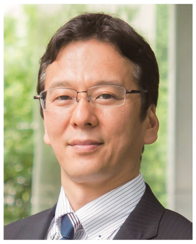

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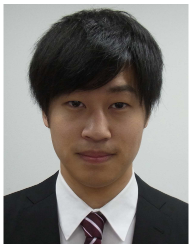

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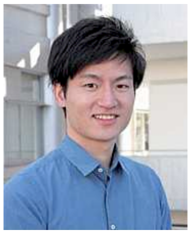

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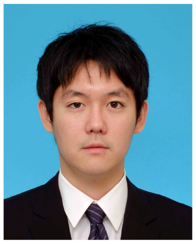

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