Spatial electricity sharing system for making city more resilient against X-Events

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Abstract: This paper extends the concept of our proposed (Yamagata and Seya, 2012) community-based disaster resilient electricity sharing system (DRESS) as a complement or alternative to a feed-in tariff (FiT) to achieve CO2-neutral transportation in cities. In our proposed system, electricity generated from widely introduced solar photovoltaic panels (PVs) is stored in the "cars not in use" in a city. For example, almost half of the cars in the central Tokyo metropolitan area are used only on weekends and thus are kept parked during weekdays. These cars represent a huge new potential storage depot if they were replaced by electric vehicles (EVs), that is, they could be used as storage batteries in a V2G system. The present study extends our proposed system in the following two senses. Firstly, different from Yamagata and Seya (2012), this paper uses actual ground area data (footprint) of each building to estimate PV supply, which may lead to more accurate estimations. The results show that although the entire electricity surplus (PV supply minus demand) could be stored without waste if 12% of the EVs not in use were utilized as storage batteries at an aggregate (city) level, there exist significant regional mismatches at the local district level. Hence secondly, based on the geographical PV supply-demand estimates, this paper analyses the possibility of local electricity sharing by looking at the geographical distribution of high-storage potential areas using a spatial clustering technique.

Key Words: Electricity sharing, PV, EV, CO2 neutral, spatial clustering.

1. Introduction

In order to realize low-carbon cities, the “Smart City” (SC) (e.g., Komninos et al., 2013[12]) concept has become popular recently, and many urban projects such as the Masdar city project (Nader, 2009[13]) have sought to implement this concept. Although the definitions of SC itself are diverse and not academically defined, it is based on a common recognition that electric vehicles (EVs) form one of the most important elements of the SC, because they could run without emitting CO2. However, it is important to note that the diffusion of EVs may increase CO2 emissions if EVs are charged with carbon intensive electricity (e.g., Perujo and Ciu, 2010[15]; Doucette and Mc Culloch, 2011[5]; Hedegaard et al., 2012[9]; Wu et al., 2012[19]). In other words, EVs need to be fully charged using renewable energy-based electricity such as solar photovoltaic panels (PVs) in order to prevent such an adverse effect. Hence, from the view point of reducing CO2 emissions, EVs and PVs must be considered in a simultaneous manner.

Thus far many studies have discussed the possibility of the PVs as a power source for EVs (e.g., Giannoulis and Yianoulis, 2012[7]). Denholm et al. (2012)[4] discussed the possible co-benefits of large scale plug-in hybrid EV and PV deployment, and Richardson (2013)[16] provides an excellent review with regard to EV-PV integration.

In Japan, after the Great East Japan Earthquake in the year 2011, a full-blown feed-in-tariff (FiT) scheme has been started. It is projected that the scheme will contribute to the increase of the share of renewable energy-based electricity in Japan. Huenteler et al. (2012)[10] evaluated the Japanese schema from German experience, and made a comment that the schema’s “political legitimacy” is important. They noted that in Germany, the legitimacy of support for PV is eroding, resulting in recent high-level calls to end the FiT and replace it with other, less generous policies. Hence also in Japan, discussing the possibility of a wide range of other schemas for looking ahead the FiT may be an important issue. In this regard, Yamagata and Seya (2012)[20] proposed a concept of a community-based disaster resilient electricity sharing system (DRESS) as a complement or alternative to FiT to achieve CO2 neutral transportation in cities. In the system, electricity generated from mass-adopted PVs is stored in “cars not in use” in a local region. For example, many cars in the central metropolitan area of Tokyo are used only on weekends and remain parked during weekdays. If some of those cars were replaced by EVs, they could be used as storage batteries in a vehicle-to-grid (V2G) system. We termed this system as “disaster resilient electricity sharing system (DRESS)” as a complement or alternative to FiT to achieve CO2 neutral transportation in cities. In the system, electricity generated from mass-adopted PVs is stored in “cars not in use” in a local region. For example, many cars in the central metropolitan area of Tokyo are used only on weekends and remain parked during weekdays. If some of those cars were replaced by EVs, they could be used as storage batteries in a vehicle-to-grid (V2G) system. We termed this system as “disaster resilient electricity sharing system (DRESS)” as a complement or alternative to FiT to achieve CO2 neutral transportation in cities.

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2. Estimation of electricity demand and supply from PVs for Yokohama

2.1 Study area

Figure 1 shows the location of Yokohama, which is the target area of this study. The city is divided into microdistricts or zones (called cho-cho-moku) which are based on the seven-digit postal code. During 2008 (our target period), Yokohama encompassed 1661 cho-cho-moku and had a total population of approximately 3.7 million.

![Fig. 1 Yokohama city in the Tokyo metropolitan area (devided into micro districts called cho-cho-moku)](http://pflow.csis.u-tokyo.ac.jp)

2.2 Method for estimating the residential demand for electricity and the supply of electricity by PVs

This subsection explains how we calculated the electricity surplus, which reflects the electricity supplied by PVs in a given area and the overall residential demand for electricity (not just that supplied by PVs) in that area.

To estimate the amount of electricity generated by PVs, we assumed that a PV was installed on the roof of each detached house in the study area. Then we calculated the amount of electricity supplied during each hour of a 24-hour day. According to Yokoi et al. (2010)[21], the hourly average electricity supply by PVs (kWh/h) can be estimated as

\[
P_V^i = I_i \times \tau \times \text{roof}^i_{\text{PV}} \times \eta_{\text{PC}} \times K_{\text{PV}} \times T
\]

where \(i(i = 1, \ldots, n)\) denotes the zone, \(I\) is the total (solar) irradiance (kWh/m²/h), \(\tau\) is the array conversion efficiency (≈ 0.1), \(\text{roof}^i_{\text{PV}}\) is the installation area (in m²), \(\eta_{\text{PC}}\) is the running efficiency of power conditioner (= 0.95), \(K_{\text{PV}}\) is the temperature correction coefficient (= 0.9221 for May through October, = 1 for the other months), and \(T\) is the performance ratio (= 0.89).

In Yamagata and Seya (2012)[20], we defined \(\text{roof}^i_{\text{PV}}\) as

\[
\text{roof}^i_{\text{PV}} = L_i \times \xi \times \iota \times l / \cos \psi
\]

where \(L\) is the land (lot) area (in m²), \(\xi\) is the building-to-land ratio, \(\iota\) is the possible area of installation on the roof (≈ 0.3), and \(\psi\) is the optimal angle of inclination (≈ 30°). However, in the current study, we used the actual ground area of each building, i.e., \(L_i \times \xi\), which was obtained from the City Planning Basic Survey of 2008. From this data set, we extracted only residential detached houses (605,436) and grouped these data according to cho-cho-moku.

To estimate Yokohama’s demand for electricity, we calculated the zonal hourly demand. The numerous methods for estimating electricity demand according to various spatial scales (national, regional, etc.) and time scales (hourly, monthly, yearly, etc.) have been summarized in several excellent review articles (e.g., Foley et al., 2010[6]; Almeshaie and Soltan, 2011[1]; Grandjean et al., 2012). Swan and Ugursal (2009) categorized electricity demand (load forecasting) models into top-down and bottom-up approaches. According to Grandjean et al. (2012)[8], bottom-up approaches, which are consistent with our focus, calculate unit energy consumption (intensity data) for a dwelling or a group of dwellings and extrapolate this value to the total housing stock.

In Japan, data on regional, hourly, electricity demand by sector (residential, commercial, transport, etc.) are not publicly available. Residential electricity demand often has been estimated by using the electric bill data from the Family Income and Expenditure Survey or the National Survey of Family Income and Expenditure of the Ministry of Internal Affairs and Communications. However, these data usually are available only monthly or yearly.

To our knowledge, only the Japan Institute of Energy (2008) provides hourly electricity intensity data (kWh/m²/h) for each of the categories of residential, office, hospital, hotel, store, and sport facility. We, therefore, used this residential-specific intensity information and multiplied it by the appropriate floor area (floor space) in each zone to estimate the hourly electricity demand; floor area data also were obtained from the City Planning Basic Survey (2008). We then summed the hourly residential electricity demand in the target cho-cho-moku to obtain the estimated overall zonal hourly residential electricity demand.

2.3 Data

Our target period was 2008; the data we gathered are summarized in Table 1. The transportation (the origin destination [OD] trip) data that we used are from the Fourth Person Trip Survey in Tokyo Metropolitan Area, which was implemented in 1998. The data are available through the People Flow Project (http://pflow.csis.u-tokyo.ac.jp/) upon request and include the OD trips by traffic mode, time of day, purpose, etc. for each cho-cho-moku. The Person Trip Survey is a national survey that focuses on people’s travel behavior during a given few days of each month, from October to December. In using these data, we assumed that people’s travel behavior is temporally stable (that is, identical for every month).

Because the number of cars in Yokohama for each cho-cho-moku is unknown, the city-level value was allocated to the cho-cho-moku and adjusted for the size of the population. Whereas we previously used estimated (aerially interpolated) values for floor and ground areas (Yamagata and Seya, 2012[20]), the current study uses actual measurements, thus probably increasing the accuracy of our estimates.
2.4 Empirical estimation

Figure 2 represents the solar irradiance of an average year for every hour of a 24-hour day in August. We used the envelope (peak value [max]) of the solar irradiance during each hour because we were focused on the maximal potential for storing surplus electricity. However, we used the average hourly values for comparison.

The estimated hourly electricity demand (including demands for heating and cooling) and PV-generated supply (maximum; average) are shown in Figure 3. The demand patterns clearly differ between months, although PV supply patterns are similar throughout the year. In summer (e.g., August), the demand from 19:00 to 21:00 is peak hours, whereas the demand during winter (e.g., January) remains fairly stable throughout the day, i.e., there is no strong peak hour. The demands during May and October are the lowest among all months because of the lack of thermal (heating and cooling) demand. By summing the hourly demand and supply, we obtained the daily overall surplus value (Fig. 4). This figure shows that during hot months (July and August) and cold months (November through March), the demand for electricity cannot be fully satisfied by using PVs, even if PVs were installed on the roofs of all detached houses. Whereas the demand is comparable to the PV supply (maximum) during some transition months (April and September), it is lower than or comparable to the PV supply (maximum and average, respectively) during other transition months (May, June, and October). In the following analyses, we used the electricity surplus of two representative months: August (high demand, high PV supply) and January (high demand, low PV supply). In Japan, January is the coldest month and August is the hottest, and the electricity demand patterns induced by the demands associated with heating and cooling, respectively, clearly differ.

3. Calculation of storage potential for electricity surplus

3.1 MATSim

In the following analysis, we needed to know [a] the number of cars parked at home during each hour (that is, the time each car arrived at home after use) and [b] the amount of battery charge consumed by each driver during his/her daily trips (that is, trip duration). For this simulation, we used the agent-based transportation simulator MATSim (http://matsim.org/). The road-network information was taken from the National Digital Road Map Database and includes sufficient data regarding road capacity, width classification, link length, number of lanes, and travel speed to perform traffic simulations in MATSim. MATSim requires a daily “plan file” for each agent (driver); we prepared these files by using the Fourth Person Trip Survey, which captured the daily movements of 722,000 people. From these data, we extracted the car trips whose origins and destinations were in Yokohama. Because the Fourth Person Trip Survey sampled approximately 2% of the population of the Tokyo metropolitan area, the plan file was replicated according to the intensity factor provided by the People Flow Project, resulting in 505,335 agents.

From the MATSim simulation, we obtained information regarding trip duration and the arrival time of each agent. Figure 5 represents the number of cars at home; “cars not in use” are always parked at home, and “cars in use” are at home once their daily trips are finished. The figure shows that most cars are back at home after 16:00. In 2008, the total number of registered cars in Yokohama was 989,125 (including light motor vehicles [only for private use]), and 51% of these cars were in use during the day of the survey. Therefore 49% of all cars were not used (that is, “cars not in use”) during the day of the survey.

3.2 Estimation results

Figure 6 depicts the estimated electricity surplus and shows that the PV-generated supply will exceed demand during the daytime in August (maximum), whereas demand will always exceed PV supply in January, except around 12:00 during the maximum PV-supply scenario. Currently in Japan, residents and firms have several economic incentives to introduce PVs but, because of the FiT, fewer incentives to introduce storage devices are available. Therefore to avoid large reverse power flows, a new scheme for storing surplus electricity must be implemented.

If all of the cars (whether in use or not) in Figure 5 were
Fig. 3 Hourly electricity demand and PV-generated supply (top, demand; middle, maximal PV-generated supply; bottom, average PV-generated supply) (black solid line, overall maximum; black dashed line, overall average; the other lines, daily values)

Fig. 4 Daily electricity demand versus PV-generated supply

Fig. 5 Number of cars at home

replaced by EVs (we assume that the EVs are Nissan Leafs, which have a battery capacity of 24 kWh and electric mileage of 8 km/kWh) that are charged with grid electricity, the carbon emission from car use (per km) would be half that of a typical gasoline-powered car, according to the current electricity supply mix in Tokyo (Nakamichi et al., 2012[14]). Therefore, to run EVs as carbon-neutral vehicles, EVs must be charged (insofar as possible) by using electricity generated from renewable energy sources, such as PVs.

Hence here, we tested how many EVs would be necessary to store the entire electricity surplus. We assumed that, when not in use, cars (EVs) could function as storage batteries to supply households with electricity (e.g., the Nissan Leaf has this option). We also assumed that the batteries of the EVs not in use were empty at 0:00 (that is, all electricity consumed the day before) and that the EVs in use were charged the quantity just consumed during their daily trips (shown as the dashed line in Figure 6) as soon as these trips were complete and the EVs had returned home. In this experiment, the DC-AC conversion efficiency loss of the electricity stored to the EV batteries is not considered.

The solid line in Figure 7 shows that 12% of the EVs not in use would be sufficient to store the electricity surplus in August during maximum solar irradiance (30% is shown as another example). Regarding other scenarios, 1% (August, average), and 0.002% (January, minimum) of the EVs not in use would be sufficient to store the associated electricity surplus.

4. Spatial local sharing of EV capacity

4.1 Spatial mismatches in storage capacity

We just showed that 12% of EVs not in use would be sufficient to store the entire electricity surplus during August at an aggregate level. But looking at the cho-cho-moku level reveals marked regional differences. The top of Figure 8 shows the geographical distribution of electricity surplus, whereas the remaining panels show the storage capacity (second, 10%; third, 30%; bottom, 50% of EVs not in use functioning as storage batteries). In Japan, most of the thermal and nuclear power stations are located in coastal areas; therefore the current electricity supply system is highly vulnerable to natural disasters, including flooding and tsunamis. Because the risk of these hazards is projected to increase due to climate change, using distributed generation of electricity to minimize these risks becomes increasingly important. We therefore propose the construction of a micro grid at the local (town or cho-cho-moku) level and “locally shared EVs (storage depots) for surplus PV-generated electricity” (in other words, local sharing of PV-generated electricity) to achieve: [1] a low-carbon, disaster-resilient electricity supply system [2] that avoids the problem of inverse power
flow. Hence it is critically important to test whether the electricity surplus and storage capacity shown in Figure 8 are matched spatially.

### 4.2 Spatial clustering by Moran scatter plot

Figure 9 shows the storage affordability (storage capacity minus electricity surplus) for each cho-cho-moku in August. In the 10% scenario, many zones are categorized as having a storage affordability of less than 0, whereas storage affordability is positive for many zones in the 30% and 50% scenarios. Increasing the ratio of EVs used for storage of surplus electricity would hinder the actual implementation of the system. Therefore, locally sharing EVs among zones is crucial because marked regional differences in storage affordability exist. For example, if a high-affordability zone (the difference of storage capacity minus electricity surplus is positive and large) is adjacent to a low-affordability zone (storage capacity minus electricity surplus is negative and large in absolute value), then these zones can locally share EV capacity.

For implementing such a local EV capacity sharing, we employed Moran scatter plot by Anselin (1996), a spatial clustering technique developed in the field of spatial econometrics. The Moran scatter plot plots the standardized affordability value against its standardized spatial lag (weighted average). A spatial lag of an affordability value is the weighted average affordability of its surrounding (contiguity) zones. Figure 10 illustrates the concept of Moran scatter plot. With both axes standardized, the Moran scatter plot can be divided into four quadrants. Quadrant I (top right corner) shows high affordability zones that are also surrounded by high affordability zones. Quadrant II (top left corner) shows low affordability zones with high affordability neighbors. Quadrant III (bottom left corner) shows low affordability zones surrounded by low affordability zones. Quadrant IV (bottom right corner) shows high affordability zones with low affordability neighbors. For simplicity, henceforth, we refer to quadrants 1 through 4 as HH, LH, LL, and HL respectively.

### 4.3 Spatial local sharing of EV capacity by Moran scatter plot

We can easily test whether each cluster is statistically significant or not (Anselin, 1995). Also, overall spatial autocorrelation can be tested using Moran’s I, which is one of the most well-known statistics used to measure spatial autocorrelation. Moran’s I lies between -1 and 1, with 1 indicating strong positive spatial autocorrelation (i.e., spatially clustered). The result of the spatial clustering using Moran scatter plot is shown in Figure 11. In the 10% scenario, a high spatial autocorrelation (Moran’s I = 0.266) was detected (significant at 1% level). This autocorrelation was improved (Moran’s I = 0.213) when we assumed that 20% of the non-used EVs were used for the storage
Interestingly, however, spatial randomness was worsened when 30% of the non-used EVs were used as the storage battery (Moran’s I = 0.220). Such result was caused by high affordable zones increasing geographically concentrated manners. Figure 12 represents the value of Moran’s I against the percentages of EVs functioning as storage batteries. Spatial autocorrelation was minimized at around 20%; hence we can interpret that the 20% is a reasonable choice in terms of both resilience and cost effectiveness.

5. Concluding remarks
Owing to the FiT, the share of electricity generated through solar power is projected to increase in Japan. A scheme to man-
large reverse PV electricity flows, which can affect existing grids, is therefore needed urgently. Herein we have presented one potential solution to this electricity storage problem. We propose the construction of a micro grid at the local (town or cho-cho-moku) level, and local sharing of EVs (storage capacity) for PV surplus to attain a low carbon, disaster-resilient electricity supply system that also avoids the inverse power flow problem.

The present study extended the DRESS system proposed in Yamagata and Seya (2012) in the following two senses. Firstly, different from Yamagata and Seya (2012), it used actual ground area data (footprint) of each building to estimate PV supply. The obtained results showed that although the entire electricity surplus (PV supply minus demand) could be stored without waste if 12% of the EVs not in use were utilized as storage batteries at an aggregate (city) level, there exist significant regional differences at the local district level. Hence secondly, based on the geographical PV supply-demand estimates, we analyzed the possibility of local electricity sharing by looking at the geographical distribution of high-storage potential areas using a spatial clustering technique called Moran scatter plot. We found that about 20% was a reasonable choice in terms of both resilience and cost effectiveness.

In future research, we are planning to optimize the distribution of spatial clusters for the local electricity sharing system using mathematical optimization and computational statistics techniques.

For the actual implementation of our proposed system, the social benefit must be estimated, and compared to its cost. The benefits estimation under uncertainty itself is not an easy task, especially when the uncertainty comes from X-event. Also, this system critically depends on the people’s cooperation and consciousness to share their EVs to store PV generated electricity surplus (or to share PV generated electricity under emergency inside the community). Such interactions may help to enhance the attachment to their community, but technically, quantifying and assessing such effect must depends on the questionnaire survey assuming the situation difficult to imagine. For this reason, a possible way for realizing this system is doing small scale social experiment, and accumulating knowledge and experience with actual observations.

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