Simulating a future smart city: An integrated land use-energy model

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HIGHLIGHTS

► The concept of land use-transportation energy model is demonstrated.
► The spatial explicit land use model is constructed for the Toyo metropolitan area.
► Several future compact/dispersion city scenarios for the year 2050 are analyzed using the model.
► Intra-day dynamics of electricity demand and supply from PV panels under two urban scenarios is simulated.
► Compact urban form may contribute to the reduction of electricity demand from the residential sector.

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ABSTRACT

Designing a future smart city (FSC) that copes with the reduction of CO2 has become one of the urgent tasks of the next 20 years. One promising approach to achieve FSC is to combine appropriate land use (compact city with energy efficient buildings and photovoltaic panels (PVs)), transportation (electric vehicles (EVs) and public transportation system) and energy systems (smart grid systems), because of the interaction between these elements. However, there are few models which simulate these elements in an integrated manner. This paper presents the concept of the integrated model, and shows the land use-energy part of the model created for the Tokyo metropolitan area, which is the largest Mega city in the world. Firstly, a spatially explicit land use model (urban economic model) is constructed for the study area, and the model is calibrated using existing statistical data. Secondly, possible future compact/dispersion city scenarios for the year 2050 are created using the model. Thirdly, intra-day dynamics (hourly) of electricity demand and supply from PVs, which is assumed to be installed to the roofs of all detached houses in the study area, under two urban scenarios is simulated. The obtained results suggest that [1] "compact" urban form may contribute to the reduction of electricity demand from the residential sector, but [2] PV-supply under the scenario may also be reduced because of the decreased share of detached houses. Hence in the compact city scenario, it is important to discuss the effective use of vacant areas in suburbs, which may be used for large PV installations, or be re-vegetated to mitigate urban heat island effects.

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1. Introduction

Reduction of CO2 and other green house gas emissions through global climate change mitigation remains an urgent global issue. Recently, in connection with the planning of low-carbon cities, many urban planners have become aware of the “compact city” concept. Newman and Kenworthy [1] analyzed the relationship between population density and gasoline consumption, and clarified that low density leads to high gasoline consumption, and high density leads to low gasoline consumption. After this seminal paper, many studies have discussed possible compact urban forms from the viewpoint of sustainable development (e.g. [2–4]). Indeed, these studies have indicated that cities with low residential density rely disproportionately on automobile transportation, and therefore CO2 reduction could be achieved by changing to a more compact urban form, which would lead to increased use of public transportation and reduced of car trip length. Now the next challenge is to test whether a compact city will also reduce CO2 emissions from residential sector [5]. CO2 emissions are usually estimated by multiplying emissions intensity based on the number of households or residential floor areas (space), and therefore a toolbox which enables us to estimate these variables under several urban forms is required.
The concept of the future smart city (FSC) has become popular recently, and many urban projects such as the Masdar city project \[6\] have sought to implement this idea. Although the definition of FSC itself is diverse and not academically defined \[7,8\], it is based on a common recognition that electric vehicles (EVs) form one of the most important elements of the FSC, because they run without emitting CO₂. However, it is important to note that diffusion of EVs may increase CO₂ emissions if EVs are charged with carbon intensive electricity (see e.g., \[9\]). Hence EVs need to be charged using renewable energy-based electricity such as photovoltaic panels (PVs) in order to prevent such an adverse effect. If EVs are completely charged only from renewable energies, the above mentioned negative correlation between population density and CO₂ emissions from the transport sector might be changed. Hence the preferable urban form such as the compact city should consider energy aspects.

Fig. 1 represents the possible interaction between land use-transportation and energy. It is noted that urban form will affect not only origin destination (OD) trip (transportation) distribution patterns but also energy demand and urban climate. Urban heat island effects may also affect electricity demand especially for cooling in summer season, but can be mitigated by strategic changes in land use such as re-vegetation in suburban areas \[10\].

Taking these interactions into account, a promising approach to simulate FSC is to combine appropriate land use (compact city with energy efficient buildings and PVs), transportation (EV and public transportation system) and energy systems (smart grid). Thus far many efforts have been devoted to development of urban models that consider the interaction between land use and transportation (e.g. \[11–14\]). However, there are few studies which attempt to model land use, transportation, and energy simultaneously.

Hence as the first step toward an integrated model, the present paper analyzes the effects of urban form on electricity demand and supply from PVs (PV-supply), which is assumed to be installed to the roofs of all detached houses in the Tokyo metropolitan area. Specifically, a large spatially explicit land use model which is constructed at the micro-district (around 1 km²) level for the whole Tokyo metropolitan area. The structure of our model is shown in Fig. 2. Major assumptions of this model are summarized as follows:

1. There exists a spatial economy whose coverage is divided into zones \(i (i = 1, \ldots, I)\).
2. The society is composed of three types of agents: household, developer, and absentee landlord. The behavior of each agent is formulated on the basis of microeconomic principles, that is, utility maximization by households and profit maximization by developers, and absentee landlords.
3. Households are divided into each of seven categories shown in Table 1.
4. Total number of households (or population) in the metropolitan area is given (closed city).
5. The households choose their locations in accordance with indirect (maximized) utility.
6. There is one residential land market and residential floor (building) market in each zone. These markets reach equilibrium simultaneously.

2.2. Household’s utility maximization behavior

In typical land use model studies, a household’s indirect utility function is specified as
The supply-demand balance is shown in Fig. 2.

### Table 1

#### Household type.

<table>
<thead>
<tr>
<th>Household types</th>
<th>$s$ (Eq. (4))</th>
</tr>
</thead>
<tbody>
<tr>
<td>[1] One-person households (65 years of age or over)</td>
<td>1</td>
</tr>
<tr>
<td>[2] One-person households (under 65 years of age)</td>
<td>1</td>
</tr>
<tr>
<td>[3] Married couple only (either of them 65 years of age or over)</td>
<td>2</td>
</tr>
<tr>
<td>[4] Married couple only (neither of them 65 years of age or over)</td>
<td>2</td>
</tr>
<tr>
<td>[6] Father and child (ren)/Mother and child (ren)</td>
<td>2.17</td>
</tr>
<tr>
<td>[7] Other types</td>
<td>2.85</td>
</tr>
</tbody>
</table>

The indirect utility function is given by:

$$V_i^h = \ln y_i - \alpha_y \ln r_i^{[\text{re}]} - \alpha_c c_i^{[\text{pr}]} ,$$

where $h$ denotes the household agent type; [re], residential use. Also, $V$ denotes indirect (maximized) utility; $y$, income per person in the household; $r$, floor rent per unit; $c^\text{pr}$, generalized cost of a private trip. Because of limitations in data availability and computational reasons, we have to make some practical assumptions. Firstly, we assume that $y$ and $c$ are fixed, which leads to a partial equilibrium model not a general equilibrium model. Second, $y$ and $c$ are identical for zones $l$ if its higher zone (i.e. municipality) $j$ is the same. Hence in this paper, we focus on the changes in $r$. By applying Roy's identity to Eq. (1), individual demand function of each good is derived as:

$$a_{i}^{[\text{re}]} = \alpha_y y_i / V_i^h, \quad \frac{c_i^{[\text{pr}]} y_i}{V_i^h} = \alpha_c c_i^{[\text{pr}]}, \quad \frac{z_i^h}{V_i^h} = \alpha y_i, \quad \text{where} \quad \alpha_y + \alpha_c + \alpha = 1, \quad \alpha > 0, \quad (2)$$

where $a$ denotes the consumption level of a residential area per person in the household; $x$, that of a private trip per person; $z$, that of composite good per person (whose price is assumed to be one). The parameters can easily be estimated by applying ordinarily least squares (OLSs) to Eq. (2). With indirect utility and some location specific attributes $q \times 1$ vector $f$ given, the location choice behavior of each household is formulated as an aggregate logit model as a

$$p_{i}^{[\text{re}]} = \frac{\exp(V_i^h)}{\sum_{i} \exp(V_i^h)}, \quad \text{where} \quad V_i^h = \beta^h V_i^{[\text{re}]} + f_i \chi_i^h, \quad (3)$$

where $\beta^h$ is a scalar parameter and $\chi_i^h$ is a $q \times 1$ parameter vector. We consider the characteristics of each household type by these parameters. The zonal aggregate demand for floor area in each zone is given by:

$$A_l^{[\text{re}]} = \alpha_y \sum_{h=1}^{H} \mathcal{N}_l^h p_{i}^{[\text{re}]} z_i^h, \quad (4)$$

where $A$ denotes zonal aggregate demand for the floor area; $s$ denote the number of persons for each household type (Table 1); and $\mathcal{N}_l^h$ denotes the total number of households of each type in the whole region.

A problem of applying this simple log-linear utility function is that it cannot properly represent a household's real preference in our study area. In the Tokyo metropolitan area, $\bar{z}_y \ln r_i^{[\text{re}]}$ and $p_i^{[\text{re}]}$ are positively correlated because people tend to live in the central area where floor rent is much higher. This positive correlation may produce a negative estimate of $\alpha_y$, which makes it infeasible for scenario analyses. Hence it is important to control the “quality” of the floor in order to avoid such omitted variable bias. None of the economic land use model literature provides a solution to this problem.

In order to conduct the quality control, we use the pure-repacking model suggested by Walsh [19]. The indirect utility function is specified as

$$V_i^h = \ln y_i - \alpha_y \ln r_i^{[\text{re}]} - \alpha_c c_i^{[\text{pr}]} ,$$

$$\bar{r}_i^{[\text{re}]} = \bar{r}_i^{[\text{re}]} / \bigg[1 + \sum_k g_{ik} \bigg] , \quad (5)$$

where $\bar{r}$ is a quality adjusted floor rent. We adopt this approach because it is natural to suppose rent (or individual demand) of floor area is differentiated by some local attributes $g$ (with parameter $\gamma$). The individual demand function for residential floor area is then given by

$$a_{i}^{[\text{re}]} = \frac{\alpha c_{i}^{[\text{pr}]}}{1 + \sum_k g_{ik}} \bigg[\frac{1}{1 + \sum_k g_{ik}} \bigg] y_i , \quad (6)$$

If $\gamma$ equals to $-1$, then Eq. (6) will come back to the demand function derived from a log linear utility function. Because Eq. (6) is nonlinear with respect to the parameters, its estimation is not straightforward. Hence we apply the nonlinear least squares to estimate $\gamma$ and $\alpha_c$ with fixed $\alpha$ $\gamma$ is set to $-0.8$ in this study based on some experiments (We varied $\gamma$ from $-1$ to $-0.1$ by $0.1$, and $-0.8$ minimized the residual sum of squares).

### 2.3. Developer’s profit maximization behavior

A developer is assumed to behave so as to maximize profit as

$$\Pi_l^{[\text{DH}]} = \max_{A_l^{[\text{DH}]}} A_l^{[\text{DH}]} - P_l^{[\text{DH}]} L_l^{[\text{DH}]} - mK_l^{[\text{DH}]} ,$$

$$A_l^{[\text{DH}]} = V_l (z_i^{[\text{DH}]})^{\mu_1} (K_i^{[\text{DH}]})^{\mu_2} , \quad (7)$$

where $[\text{DH}]$ denotes the behavior of developer agent. Also, $\Pi_l^{[\text{DH}]}$ denotes a profit function of the developer; $A_l^{[\text{DH}]}$, floor area which
the developer supplies; \( L_{i}^{DH} \), land area supplied to the developer; \( p_{i}^{re} \), land rent per unit; \( m \), the material price for construction; \( K \), material inputted for the production of floor service; \( \mu_{1}, \mu_{2}, \nu \), parameters (\( 0 < \mu_{1} + \mu_{2} < 1 \)).

Solving this maximization problem yields the following floor supply function and land demand function (\( re \) is omitted here)

\[
A_{i}^{DH} = \phi_{3}: r_{i}^{re}: \eta_{i}^{re} \cdot p_{i}^{re} \cdot L_{i}^{DH} = \phi_{3}, \eta_{i}, r_{i}^{re} \cdot p_{i}^{re}, L_{i}^{DH}.
\]

The parameters \( \phi_{3}, \phi_{3}, \phi_{3} > 0 \) can be obtained by calibration (back transformation) to reproduce the observations. \( \mu_{1}, \mu_{2} \) can be estimated by OLS based on the following relationship:

\[
p_{i}L_{i}^{DH} = \mu_{1}r_{i}^{re}A_{i}^{DH}, \quad \tilde{m}k_{i}^{DH} = \mu_{2}r_{i}^{re}A_{i}^{DH}.
\]

2.4. Absentee landlord’s utility maximization behavior

An absentee landlord in each zone is assumed to behave so as to maximize profit, given by the following equation:

\[
\Pi = \prod_{i}^{[LH]} = p_{i}^{re}L_{i}^{Hi} - C(L_{i}^{Hi}),
\]

where \([LH] \) denotes the behavior of landlord agent. Also, \([LHi] \) denotes a profit function of the landlord; \([LHi] \), residential land supply; \([C(*)] \), and a cost function, which is the cost of maintaining the land. In this study, \([C(*)] \) is specified as

\[
C(L_{i}^{Hi}) = -\sigma T_{i}^{PV} \ln \left(1 - \frac{L_{i}^{Hi}}{L_{i}^{PV}}\right),
\]

where \( T_{i}^{PV} \) denotes the available area of the residential land supply and \( \sigma \) is a parameter which is obtained by calibration to reproduce the observations.

2.5. Market equilibrium condition

An equilibrium state of an urban economy is defined by two conditions [14]. One is that no household has any incentive to relocate or to change its location (location equilibrium) expressed as

\[
\sum_{i}N_{i}^{H} = N^{H}.
\]

The other condition is demand–supply balancing, defined as

\[
A_{i}^{H} = A_{i}^{DH}, \quad L_{i}^{H} = L_{i}^{Hi}.
\]

2.6. Energy model

Using the projected land and floor area, we simulate the electricity demand and PV-supply.

For the estimation of demand, we employed a unit electricity demand (kW/m^2/h) used by the Japan Institute of Energy [20], which is multiplied by the “floor area” derived from the land use model. We calculate the demand for January and August. The intensity of January includes heating demand, while that of August includes cooling demand.

For the estimation of PV-supply, we assume that PVs are installed to the roofs of all detached houses in the study area. The ratio of detached houses is estimated using the logistic regression model with explanatory variables distance to the train station and the share of each household type except type 7 in order to avoid multicollinearity problems. In this study, we suppose a fine day in August and January. Following Yokoi et al. [21], the hourly average electricity supply by PVs (kW h/h) in each zone can be estimated as

\[
PV_{i} = I \times \times L_{i}^{PV} \times \eta_{PV} \times K_{pt} \times T.
\]

where \( I \) denotes total (solar) irradiance (kW h/m^2/h); \( \tau \), array conversion efficiency (=0.1); \( L_{i}^{PV} \), installation area (m^2); \( \eta_{PV} \), running efficiency of power conditioner (=0.95); \( K_{pt} \), temperature correction coefficient (=0.9221 for May–October,=1 for the other months); \( T \), performance ratio (=0.89), \( I \) is defined by using METPV-2 database [22], and we use the measurement at “TOKYO”. \( L_{i}^{PV} \) is defined as

\[
L_{i}^{PV} = L_{i}^{PV} \times \xi \times i \times 1/\cos \psi,
\]

where \( \xi \) denotes the building-to-land ratio; \( i \), possible area of installation on the roof (=0.3); \( \psi \), optimal angle of inclination (=30°).

3. Scenario analysis

3.1. Study area

Fig. 3 represents the study area (the Tokyo metropolitan area). The number of zones in the Tokyo metropolitan area is 22,603, and the average zonal area and its standard deviation is 0.70 and 2.48 (km^2), respectively. The total population was about 3.6 million in 2005.

3.2. Data

We gathered data for the year 2005. The data is summarized in Table 2. Some variables that could not be prepared were predicted. Zonal representative values for land rent and floor rent were predicted using Kriging [23]. Also, land and floor areas of higher zones are allocated to their micro districts based on the (standardized) product of population number and area.

3.3. Model calibration

For the quality control variables for the residential buildings, we employed \( \gamma_{1} \): average slope (angle), \( \gamma_{2} \): distance to the nearest station (m), and \( \gamma_{3} \): retail annual sales (million yen). Table 3 indicates that parameter estimates of these variables are all statistically significant at least 10% level. For introducing the location specific attributes to the location choice model, we employed the following variables: logarithm of the area (km^2), average elevation (m), average slope (angle), liquefaction risk (from 0: no risk to 3: high risk), distance to the nearest station (m), the probability of intensity 6
Table 2
Socio-economic data.

<table>
<thead>
<tr>
<th>Data</th>
<th>Data source</th>
<th>Year</th>
<th>Agency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of population</td>
<td>National census</td>
<td>2005</td>
<td>MIC</td>
</tr>
<tr>
<td>Number of employees</td>
<td>National census</td>
<td>2005</td>
<td>MIC</td>
</tr>
<tr>
<td>Total available time/Wage rate</td>
<td>Surveys on time use and leisure activities</td>
<td>2006</td>
<td>MIC</td>
</tr>
<tr>
<td>Income</td>
<td>Statistical survey of actual status for salary in the private sector</td>
<td>2007</td>
<td>National Tax Agency</td>
</tr>
<tr>
<td>Land rent</td>
<td>Officially assessed land price</td>
<td>2005</td>
<td>MLIT</td>
</tr>
<tr>
<td>Floor rent</td>
<td>Provided by a private company</td>
<td>2005</td>
<td>At home corp.</td>
</tr>
<tr>
<td>Land area</td>
<td>Fixed property tax cadastre</td>
<td>2005</td>
<td>MIC</td>
</tr>
<tr>
<td>Floor area</td>
<td>Fixed property tax cadastre</td>
<td>2005</td>
<td>MIC</td>
</tr>
<tr>
<td>Material price for construction</td>
<td>Statistics on building material and labor demand/building construction</td>
<td>2006/</td>
<td>MLIT/Construction Research</td>
</tr>
<tr>
<td>Material inputted for production of floor</td>
<td>Statistics on building construction</td>
<td>2008</td>
<td>Institute</td>
</tr>
</tbody>
</table>

MLIT: Ministry of Land, Infrastructure, Transport and Tourism, Japan.
MIC: Ministry of International Affairs and Communications, Japan.

Table 3
Parameter estimates.

(a) Demand function

<table>
<thead>
<tr>
<th>Type</th>
<th>Coef.</th>
<th>t</th>
</tr>
</thead>
<tbody>
<tr>
<td>HH</td>
<td>0.06050</td>
<td>101***</td>
</tr>
<tr>
<td>I</td>
<td>-0.05058</td>
<td>-4.01***</td>
</tr>
<tr>
<td>2</td>
<td>-0.04238</td>
<td>-1.824***</td>
</tr>
<tr>
<td>7</td>
<td>0.06827</td>
<td>6.752***</td>
</tr>
<tr>
<td>4</td>
<td>0.09228</td>
<td>13.4***</td>
</tr>
<tr>
<td>Dev.</td>
<td>0.2940</td>
<td>211***</td>
</tr>
<tr>
<td>I²</td>
<td>0.1067</td>
<td>548***</td>
</tr>
</tbody>
</table>

(b) Location choice model

| Intercept | -36.61 | -19.8*** |
| Log(area) | 0.4380 | 65.8*** |
| Indirect-utility | 1.729 | 10.7*** |
| Elevation (avg.) | -0.0004933 | -2.04*** |
| Slope (avg.) | -3.908 | -7.63*** |
| Liquefaction risk | -0.08763 | -8.84*** |
| Dist. to the nearest sta. | -0.0002758 | -25.8*** |
| Quake risk | -0.05622 | -1.07 |
| Annual sales of the retailers | -0.00001275 | -2.79*** |
| Floor area ratio | 0.001092 | 15.8*** |

(c) Detached houses share estimation model

| Intercept | 8.336 | 83.0*** |
| Dist. to the nearest sta. | 0.0001495 | 19.6*** |
| Share of type 1 | -14.04 | -42.2*** |
| Share of type 2 | -12.50 | -112*** |
| Share of type3 | 2.644 | 7.98*** |
| Share of type 4 | -14.54 | -53.7*** |
| Share of type 5 | -7.028 | -50.7*** |
| Share of type 6 | -16.21 | -42.5*** |
| Adjusted R² | 0.598 | 18519 |

1 Significant at 10%.
2 Significant at 5%.
3 Significant at 1%.
4 Significant at 0.1%.

---

suggestions that all of these variables except for earthquake risk in the location choice model are statistically significant to at least the 5% level, and the signs are all intuitively acceptable.

For the scenario analysis below, we added a constant to the location choice model, which ensured a 100% fit to the observations (called constant adjustment, which is one of the typical practical solutions for future projection models). This term indicates an additional hidden location specific effect, which is assumed to be fixed in the future. The same procedure is taken for detached houses share estimation model.

3.4. Scenario creation

For creating the 2050 scenario, we assume that the number of each household type will change to [1]: 2.07, [2]: 1.07, [3]: 1.39, [4]: 0.66, [5]: 0.69, [6]: 1.32, [7]: 0.85 (ratio to the current number), which is estimated by log-linear extrapolation of estimates for the year 2030 produced by the National Institute of Population and Society Research, Japan.

The Tokyo Metropolitan Area, which is still by far the largest Mega-city in the world, is extremely vulnerable to climate risks (e.g. flooding) because much important infrastructure is concentrated near the bay area. Climate research projects the increase of flooding risks in Tokyo due to climate change as well as Tsunami from future big earthquakes. Compact cities are not necessarily more vulnerable to climate and disaster risks, and therefore we need to consider appropriate land uses that are more resilient to climate risks. In this study, we compare the dispersion city scenario versus the compact city scenario to consider the co-benefits of climate change mitigation and adaptation measures.

The former dispersion city scenario is assumed to be the business as usual (BAU) scenario. The population density in the dispersion city scenario is shown in Fig. 4. For the latter, we assume that available residential land is restricted by 50% if the zonal centroid’s distance to the nearest station is over 500 m, which will correspond to the shrinkage land available for urbanization. Moreover, we assume that households will get a subsidy if they live around the train stations (less than 250 m from the train stations). The amount of subsidy is just canceled out by the fixed property tax imposed to the high liquefaction risk (from 0: no risk to 3: high risk) zones whose risk score shown in Fig. 5 is two or three.

The upper side of Fig 6 indicates the population and floor area distribution under the compact city scenario as a ratio to the dispersion city scenario, that is, (compact/dispersion). It is noted that the number of population and floor area increases in the zones around train stations except for where liquefaction risk is high. On the other hand it decreases in high liquefaction risk zones. The ratio (compact/dispersion) for both population and floor area
is within the range from 0.8 to 2, and therefore we can say that this compact city scenario for 2050 is realistic.

The lower side of Fig. 6 shows floor area as a ratio to the land area under two urban form scenarios, representing “actual” floor land ratio (FAR), proxy to the number of stairs. It is noted that this value will increase around train stations under the compact city scenario, reflecting the increase of high-rise building in such zones.

3.5. Simulating electricity supply by PV

Using the projected floor area for these two urban forms, we calculate the regional “hourly” electricity demand and PV-supply. In Japan, such regional electricity demand and supply data is not publicly available; hence estimating hourly demand and PV-supply is quite important for policy making purposes.

By summation of hourly demand and PV-supply, we have the daily values (Fig. 7). Fig. 7 suggests that although the difference is slight, demand under the compact city scenario is less than that of the dispersion city. It is interesting to note that in the compact city scenario, PV-supply will reduce compared to the dispersion city scenario. These results are natural for our setting because land is regulated in the suburban and high disaster risk zones (see also Fig. 8), which leads a decrease in detached houses with PVs. Hence in the compact city scenario, it is important to discuss the effective use of vacant areas in suburbs and high risk zones, such as the introduction of large PV installations or re-vegetation.

The spatial explicit model enables us to map regional differences in electricity surplus. Fig. 8 represents the spatial distribution of the electricity PV-supply as a ratio to demand. In this paper, we show the result only for August because the distribution for January is very similar. It is noted that demand exceeds PV-supply around the train stations and the center of Tokyo, while PV-supply may exceed demand for all other zones. After the Great East Japan Earthquake, many Japanese private companies have begun to pay attention to the potential of low-rent land in suburban regions, which had been abandoned, to install large PV plants. This potential may be measured as a function of land rent, demand and solar irradiance. Hence the obtained results can be a useful measure of PV potential.

Fig. 9 indicates hourly demand and PV-supply. Demand exceeds PV-supply from night to morning. However in the day time, PV-supply may be sufficient to fulfill the total demand. Hence
projecting the required battery storage for each zone using Fig. 8 is an important issue. The peak supply in January may exceed that of August due to the temperature correction coefficient. Yamagata and Seya [24] report an analysis for Yokohama city assuming that EVs, which are diffused, are used as the battery storage. However, their analysis is only for the current urban form, and therefore we have to develop an integrated land use-transportation-energy model for combining these results in future research.

Fig. 6. (a) Population distribution under the compact city scenario as a ratio to the dispersion city scenario (upper left). (b) Floor area distribution under the compact city scenario as a ratio to the dispersion city scenario (upper right). (c) Floor area as a ratio to land area under the dispersion city scenario (lower left). (d) Floor area as a ratio to land area under the compact city scenario (lower right).

Fig. 7. Electricity demand and supply from PV.
4. Concluding remarks

We have developed an integrated land use-transportation-energy model for assessing the possible renewable energy implications. We have analyzed the effects of urban forms, “compact” and “dispersion,” on household’s electricity demand and supply from PVs that are assumed to be installed to the roofs of all detached houses in the Tokyo metropolitan area. As the urban “compact” form scenarios, we considered not only “compact” urban form but also land use regulation based on disaster risk, as it is becoming more important to consider “co-benefits” of climate change measures. The results suggest that “compact” urban form can reduce the electricity demand from the residential sector comparing with “dispersion” one, but the “dispersion” urban form has more PV supply potential due to detached houses.

There are many future works remaining. Firstly, we have to develop a model to implement transport model at micro district scale for the whole Tokyo metropolitan area. We are planning to develop an agent-based land use-transportation model, but it is quite data demanding and computationally difficult. Secondly, for improving the accuracy of PV supply potential assessments at the household level, we are creating a detailed 3D digital surface model (DSM). By combining such data with hourly observed radiation data, we can estimate dynamic solar irradiance and corresponding PV-supply more realistically.

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