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Regional Analysis and Evaluation Method for Assessing Potential for Installation of Renewable Energy and Electric Vehicles †

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Abstract: Many countries are adopting renewable energy (RE) and electric vehicles (EVs) to achieve net-zero emissions by 2050. The indicators of RE and EV potentials are different. Decision-makers want to introduce RE and EVs; however, they need a method to find suitable areas. In addition, this is required in the time-series analysis to provide a detailed resolution. In this study, we conducted a time-series analysis in Japan to evaluate suitable areas for the combined use of RE and EVs. The results showed the surplus RE areas and shortage RE urban areas. The time-series analysis has quantitatively shown that it is not enough to charge EV batteries using surplus RE. Moreover, a ranking methodology was developed for the evaluation based on electric demand and vehicle numbers. This enables the government's prioritization of prefectures and the prefectures' prioritization of municipalities according to their policies.

Keywords: PV; EV; time-series evaluation; renewable energy

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1. Introduction

Due to global warming, there has been a shift away from fossil fuel-based power generation and automobiles. There has been a move towards renewable energy and the introduction of electric vehicles that use this electricity. In Japan, the power generation and transport sectors account for 58.3% of total CO_2 emissions [1]; therefore, introducing RE and EVs can make a significant contribution to CO_2 reduction. However, RE faces challenges such as time variability and regional unevenness. For example, photovoltaic (PV) systems generate electricity during the day but not at night, making it impractical to rely solely on PV systems without storage batteries and alternative power sources. In addition, renewable energy (RE) potential is often higher in rural areas, while demand is concentrated in urban areas. To bridge this gap, it is necessary to charge vehicles with electricity in rural areas and discharge it in urban areas at night. Since cars used for commuting are typically parked during the day, their energy storage potential is generally high, creating a synergistic effect when introducing RE and EVs. Consequently, many studies have explored this integration.

Mengyu et al. investigated the combined use of RE, electric demand, and EVs to form an energy system, assessing the impact on EVs and the grid under the assumption that all electricity is provided by RE in Australia [2]. Su et al. assessed the impacts of increased charging load on New Zealand's distribution network caused by the widespread adoption of EVs [3]. The study used the level of charging demand and full charging of EVs connected to the grid as optimization conditions. These two studies are technical journal papers that evaluate the impact on the grid of an integrated system of RE and EVs. They do not include the point of introducing regional characteristics. Elli conducted a demonstration test for EV charging with RE [4], using an algorithm to fluctuate electricity prices based on renewable electricity generation forecasts, encouraging people to charge their EVs during peak renewable electricity generation periods. This approach led to a 30% reduction in CO_2 emissions generated during charging and enabled more than 40% of the participants to save up to 70 EUR/year on their electricity bills for charging. This is because EVs were charged during the cheaper times when there is a lot of RE generation. The results of this test show the quantitative benefits of integrated systems. Therefore, it would be desirable for such demonstrations to be carried out all over the world; however, it is not realistic. Kobashi et al. evaluated the integrated system for its environmental and economic efficiency in Kyoto [5] and in Japanese housing [6,7]. In addition, some other Japanese-language papers exist [8–11]. However, decision-makers need a method that allows them to quantitatively compare regions across the country or within prefectures in order to select regions for the introduction of integrated systems of RE and EVs. Moreover, the studies that have been conducted in Japan have been on a macro or regional scale. While macro-scale studies are useful for understanding the overall impact, they do not provide detailed analyses, often considering RE only in terms of kWh without addressing its time variance. At the regional scale, various methods such as microgrids, smart grids, and dynamic pricing are being considered. However, identifying suitable areas for RE and EV integration, which are unevenly distributed across regions, is crucial. This study aims to clarify the boundaries between urban and rural areas in Japan and develop methods for introducing RE and EVs in suitable areas.

In this study, a time-series analysis was conducted in 45 prefectures to identify areas suitable for the combined use of RE and EVs. The methodology was then refined and applied in Ibaraki Prefecture to examine priority introduction points for RE and EVs according to local policies.

2. Time-Series Evaluation

2.1. Methods and Data Settings

The net electric energy P_{net} was calculated by combining electric demand D, electric consumption of the car F_{e}, PV generation P_{pv}, and the charge used at a given time P_{c}, as shown in Equation (1):

$$P_{\text{net}} = D + F_{\text{e}} - P_{\text{pv}} - P_{\text{c}} \tag{1}$$

Electric demand D was estimated as the hourly electric demand for each prefecture based on the annual electric demand by prefecture, provided by the METI Electricity Statistics [12], and the hourly electric demand for each area. Figure 1 shows the comparison of demand in Osaka, Ibaraki, and Tokyo. Ibaraki and Tokyo, both within the same TEPCO service, exhibit similar demand patterns, although their maximum values differ due to prorating effects. Osaka shows a different pattern, owing to its higher demand and different areas.

PV generation P_{pv} was the only form of RE used in this chapter, with hourly solar radiation based on average yearly data, an optimum tilt angle, and an azimuth angle of 0°, centered on the prefectural capitals. Figure 2 shows a comparison of solar radiation in Osaka, Ibaraki, and Tokyo. The area was estimated to introduce PV generation based on the potential of each prefecture, using data from the Ministry of the Environment, which was used as the hourly generation potential [13]. The reference used the following equation for the estimation of PV potential in each area:

$$\textit{Install potential} = \textit{Available Area} \times K \tag{2}$$

where the Available Area is the available roof space over 150 m^2, and K is the constant utilization factor per unit area (0.0833 kW/m^2). As shown in this figure, Ibaraki demonstrates a similar trend to Tokyo and a different trend to Osaka because Tokyo is a neighboring prefecture; however, Osaka is about 500 km away from them.

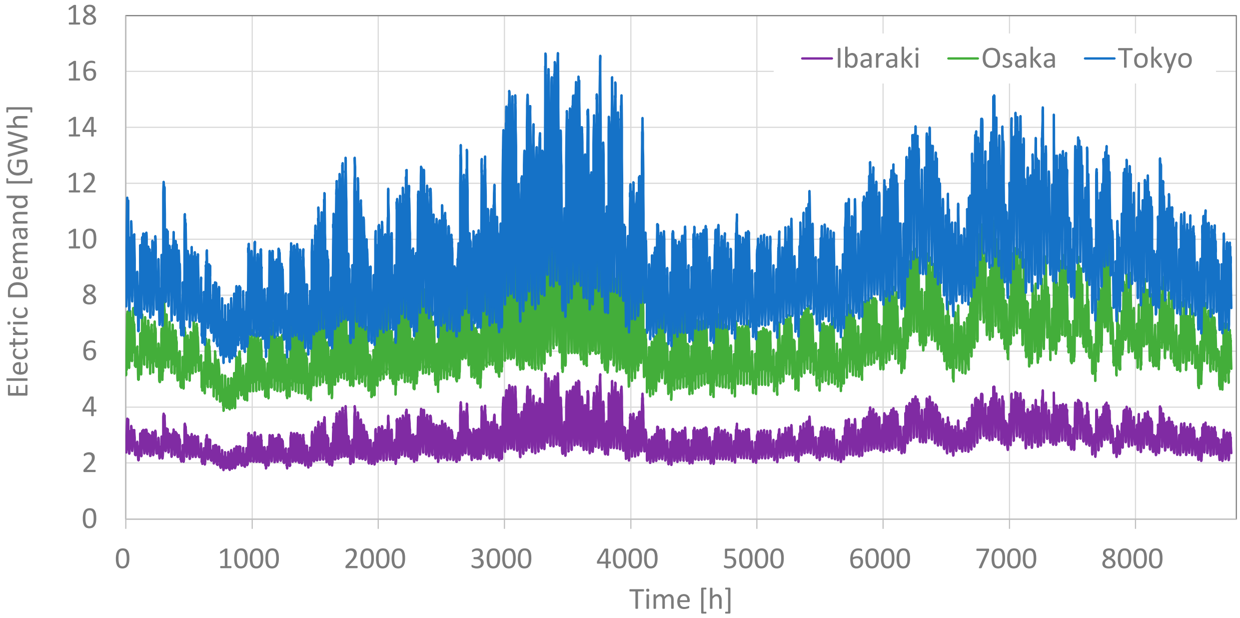


Figure 1. Comparison of demand in Osaka, Ibaraki, and Tokyo.

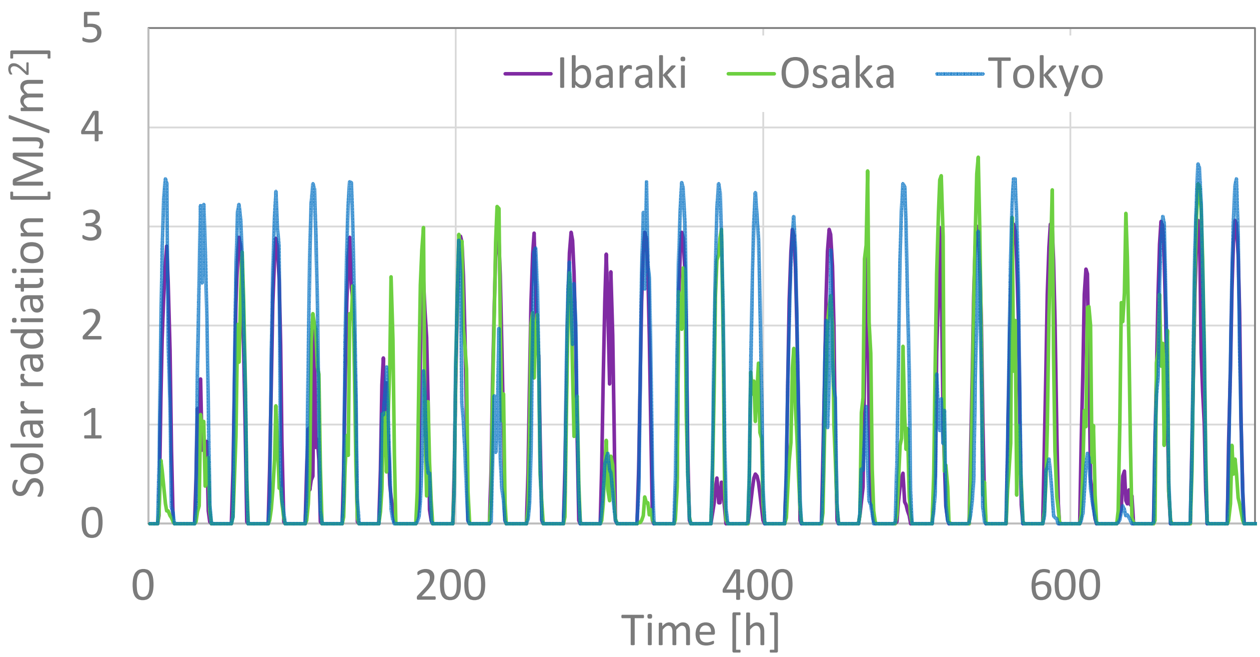


Figure 2. Comparison of solar radiation in Osaka, Ibaraki, and Tokyo.

The number of EVs was estimated based on the total number of cars registered in each prefecture [14]. The EV penetration rate was set, with the battery capacity per car being 62 kWh and an initial charge set at 50% of the capacity. The stopping rate was 90% [15], and the electric consumption F_e was 7 km/kWh. The charge and discharge current limits and the percentage of capacity available were variable.

In this study, two cases were set as conditions. In the maximum introduction case, where the charging and discharging current limits were 50 kW, the percentage of capacity available for charging and discharging was 80%, and the EV penetration rate was 100%. In the charge-restriction case, the charging and discharging current limit was 6 kW, and the capacity available for charging and discharging was limited to 50% of the maximum installation case.

2.2. Results and Discussions About the Relationship Between PV Potential and Demand in Each Area

Figure 3 shows the relationship between PV potential and demand. These are the macroscopic results of the total yearly potential and demand in each prefecture. The red dashed and dotted lines represent the average demand (17.2 TWh) and median demand (11.2 TWh), the blue dashed line represents the average RE potential (15.0 TWh), and the green line represents the equilibrium line between demand and potential. In urban areas such as Tokyo, Osaka, and Kanagawa, demand considerably exceeds RE potential. Aichi and Chiba, also having high demand, show substantial RE potential. Ibaraki and Tochigi, despite their proximity to Tokyo, fall below the green line, indicating that RE potential exceeds demand and that they can supply Tokyo.

Before examining these areas in detail, we calculated the macro-level results for Japan. The annual demand in Japan is 820 TWh, while the annual potential is 845 TWh. This indicates that the RE potential of Japan is higher than the demand. With perfect storage, the entire demand can be met using RE. However, as shown in Figure 3, there are regional differences in RE potential and demand, and it is important to collaborate with each prefecture.

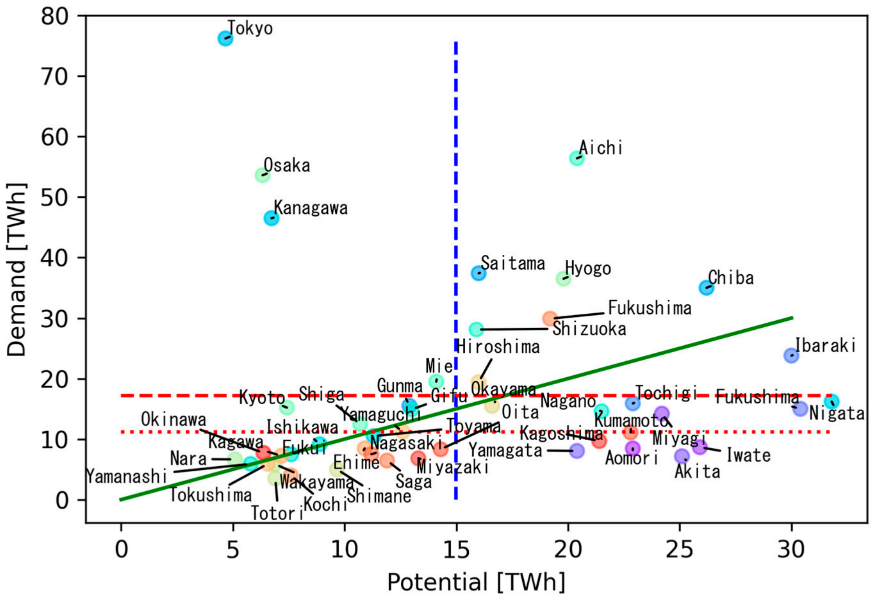


Figure 3. Relationship between the PV potential and demand, reprinted from Ref. [16].

2.3. Results and Discussions About Self-Sufficiency in Each Area

Figure 4 shows self-sufficiency in the maximum introduction case. A total of 25 out of the 45 prefectures, including Ibaraki, maintained negative net electricity consumption for all periods, indicating a self-sufficiency rate of 100%. All prefectures, even those with high demand such as Ibaraki and Tokyo, reached the upper limit of their recharging capacity, indicating sufficient RE potential for the number of automobiles owned. However, Tokyo experienced 4371 h where net electricity consumption was positive due to its high demand, indicating a self-sufficiency rate of 50.1%.

Figure 5 shows the difference in self-sufficiency in the maximum introduction and charge-restriction case. The number of prefectures with negative net electricity consumption for all hours reduced to three. In Ibaraki Prefecture, 52 h exhibited positive net consumption, resulting in a 99.4% self-sufficiency rate. The amount of charge/discharge current per hour was constrained to 6 kW from 50 kW; the number of prefectures with 100% self-sufficiency remained unchanged, staying at three. However, in prefectures with high demand, such as Tokyo and Osaka, the number of hours with positive net consumption increased by tens of hours. Prefectures with high demand were vulnerable to fluctuations as small as one hour. The charging capacity has a significant impact on the self-sufficiency rate of a prefecture. When the depth of discharge (DoD) of the battery decreased from 80% to 50%, the self-sufficiency rate was affected. This suggests that the self-sufficiency rate decreases significantly depending on the number of EVs and the participation rate.

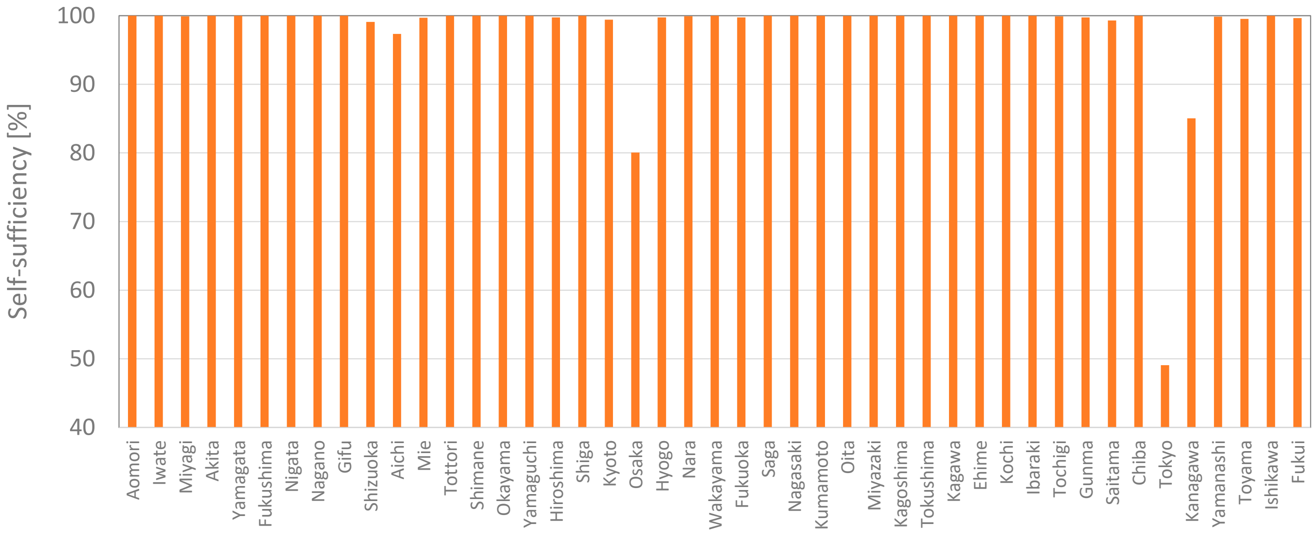


Figure 4. Self-sufficiency in each area.

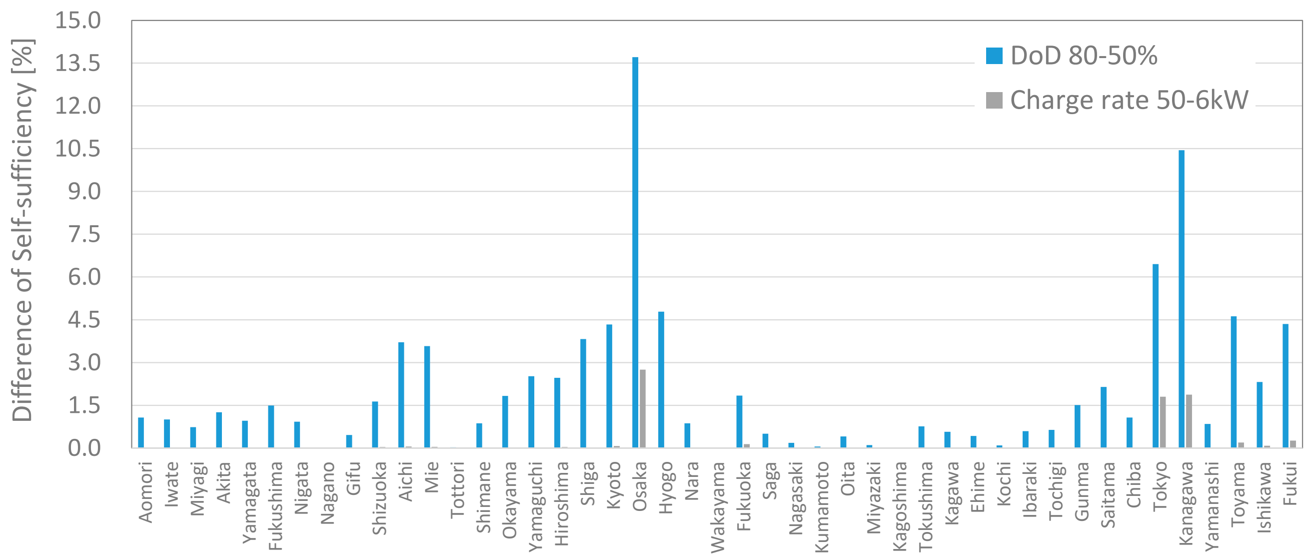


Figure 5. Difference in self-sufficiency in each case.

This analysis is optimistic because it assumes that all the cars in each prefecture will be replaced by EVs. The number of electric vehicles is an important factor that affects the electricity used for charging, and the results change depending on this number. However, the number of vehicles in the future is uncertain and difficult to predict. These results are useful for policy planning to introduce more electric vehicles.

3. Regional Analysis of RE and EVs in Ibaraki

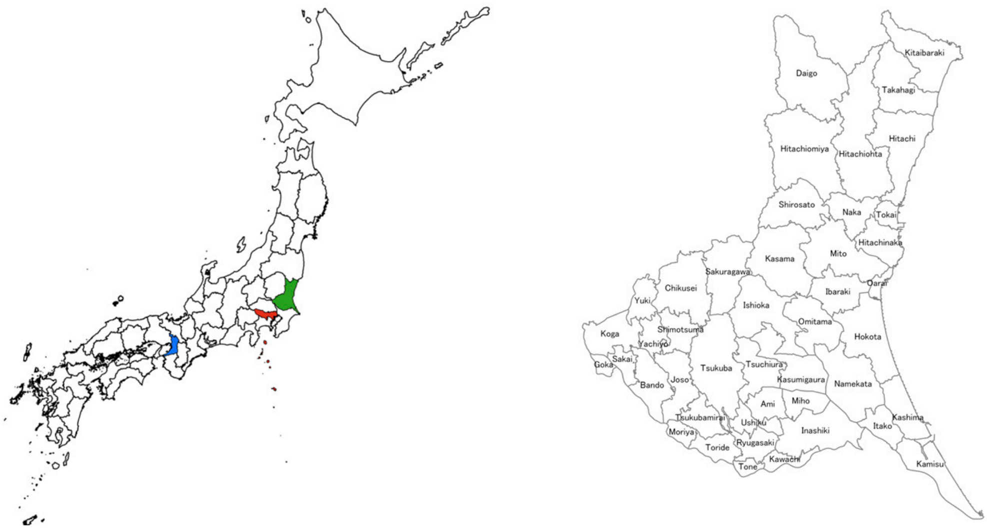
3.1. Outline of Regional Analysis in Ibaraki

The potential for combining RE and EVs in the target areas was assessed. GIS was used to visually display information and integrate and analyze it across multiple sectors, such as electric demand and the number of EVs. For this analysis, mesh data were used to reveal information dependent on regional characteristics. The term mesh data refers to a regional grid system defined by longitude and latitude for digitizing information on a map and obtaining various statistical information [17]. Tertiary mesh parcels with a side length of 1 km were used in this study.

This study used e-Stat 1 km mesh data [18], which included the population and number of households in Ibaraki Prefecture. Figure 6 shows a map of the prefecture location and its regions. Ibaraki Prefecture (green area) is a suburban area about an hour's train ride from Tokyo (red area). The population is high in the southern part which is close to Tokyo. The prefectural government office is located in Mito. Each piece of information in the mesh was calculated using the pro rata method, as described by Onodera et al. [19]. The estimation formula for the pro rata method is as follows:

$$E_{\text{mesh}} = E_{\text{TA}} \times x_{\text{mesh}} / x_{\text{TA}} \quad (3)$$

where E is the estimated element, x is the activity indicator, the subscript mesh represents the element for each mesh, and TA represents the element in the upper region, such as the city or province that encompasses the mesh.



(**a**) (**b**)

Figure 6. The location and regions of Ibaraki Prefecture. (**a**) Japan map (Ibaraki: green, Tokyo: red, Osaka: blue); (**b**) Ibaraki Prefecture map.

For the effective use of electricity, it is preferable to promote the introduction of each of these elements in locations where both RE potential and the number of EVs are high. However, in previous evaluations, it was not possible to evaluate indicators with different units, such as 'amount of electricity' and 'number of vehicles'. This study performed a quantitative evaluation of the different indicators by ranking the mesh regions based on their RE introduction potential and the number of EVs per mesh. Moreover, we identified suitable sites for the combined use of RE and EVs in the target area.

3.2. Vehicle Settings

Estimates were made for the number of vehicles present in each 1 km mesh in the target area, under the assumption that all vehicles in widespread use as of 2022 have been replaced by EVs. This assumption was used to estimate the EV introduction potential. The number of vehicles in each mesh was calculated by adding two indicators, private cars and company cars, as shown in Equation (4):

$$Car_{\mathrm{mesh}} = h_{\mathrm{mesh}}/h_{\mathrm{pref}} \times Car_{\mathrm{city,p}} + O_{\mathrm{mesh}}/O_{\mathrm{pref}} \times Car_{\mathrm{city,c}} \tag{4}$$

where *Car* represents the total number of vehicles, the subscript mesh represents the number of vehicles per mesh, and *city* represents the number of vehicles per municipality. In addition, p represents private cars, and c represents company cars. The number of households and establishments was used for prorating to the mesh, indicated by *h* and *O*, respectively, with subscripts mesh and pref representing the number of households and establishments per mesh and county-wide, respectively. The number of households used for prorating was obtained from the number of households [17] and establishment data [18] provided by e-Stat. The number of vehicles used was the number of vehicles owned by the municipality [20] provided by the Kanto Transport Bureau.

This study also assessed the impact of replacing taxis with EVs. For this purpose, estimates were made for the number of vehicles in each of these categories. With regard to the estimation of EV taxis, a weighted proportion was assigned to areas around stations. According to a taxi user survey [21], 70% of users board and alight at taxi stands located in front of stations and other taxi stands. Therefore, 70% of the total number of taxis [21], as provided by the Kanto District Transport Bureau, was assumed to be distributed within a 1 km radius of the station and prorated based on the population. The remaining 30% was divided proportionally by the population in areas beyond 1 km from the station. In addition to the electrification of taxis, this study considered the electrification of buses. Estimates were made for the number of buses, and the EV potential was calculated.

For this estimation, it was assumed that buses operate along bus routes as indicated in the land data [17], and the population within the mesh along these bus routes was used to proportion the population. The number of buses used in the estimation was based on data provided by the Kanto Transport Bureau's values [20].

3.3. RE Potential and Demand Setting and Analysis

In this analysis, photovoltaic and wind power were considered as RE sources, with the respective data provided by REPOS [12].

Regarding the electric demand, calculations were performed by proportionally distributing the electricity listed in the Prefectural Energy Consumption Statistics. Only the tertiary industry and hypothetical electric demands were extracted for this calculation, assuming that electricity would be supplied to universities, public institutions, and households. To account for the respective factors of households and establishments, the mesh was prorated by weighting the number of employees and the population in that mesh. The estimation equation is provided in Equation (5).

$$E_{\mathrm{mesh}} = P_{\mathrm{mesh}}/P_{\mathrm{pref}} \times E_{\mathrm{h}} + O_{\mathrm{mesh}} \;/\; O_{\mathrm{pref}} \times E_{\mathrm{t}} \tag{5}$$

where *E* represents electric demand, with subscripts mesh, h, and t representing the electric demand per mesh, tertiary industry, and household, respectively; *P* and *O* represent the population and number of employees, respectively, with the subscripts mesh and pref representing the totals per mesh and in the county, respectively.

3.4. Evaluation Method: RE Potential and Demand Setting and Analysis

We conducted a ranking evaluation based on the estimates derived from the data. The evaluation was performed for the two cases listed below.

Case 1: Regional evaluation on the supply side

In the combined use of RE and EVs, it is essential to introduce them in a balanced manner, as RE serves as the supply power and EVs absorb fluctuations. Therefore, regions that only have a large RE potential or a large number of EVs are not suitable for the combined use of RE and EVs. Therefore, this assessment first focused on the compatibility between supply capacity and the ability to absorb supply fluctuations and then assessed regions suitable for the combined use of RE and EVs. The RE potential was used as the supply capacity, while the potential of the number of EVs (including taxis and buses) was used as the absorbing capacity of supply fluctuations. The evaluation equation is shown in Equation (6).

$$N_{\text{mesh}} = \text{RANK}(N_{\text{pv}} + N_{\text{WT}} + N_{\text{car}} + N_{\text{Bus}} + N_{\text{Taxi}}) \tag{6}$$

where N represents the ranking in all meshes; PV, WT, Car, Bus, and Taxi represent the potential rankings for PV, wind, private EVs, company cars, electric buses, and electric taxis, respectively. As per the above equation, the combined potential on the supply side was determined by adding the ranks of RE and EVs for each mesh and then ranking the resulting values.

Case 2: Regional assessment including the demand side

The assessment in Case 1 focused only on RE and fluctuations in its generation potential in terms of supply power. However, the introduction of RE and EVs must also consider the electric demands of each region. Therefore, a ranking assessment was conducted based on the ranking of the annual power and EV introduction potential of each mesh, as shown in Equations (7) and (8).

$$N_{\text{elect}} = \text{RANK}(P_{\text{pv}} + P_{\text{WT}} - W_{\text{mesh}}) \tag{7}$$

$$N_{mesh} = \text{RANK}(N_{\text{elect}} + N_{\text{car}} + N_{\text{Bus}} + N_{\text{Taxi}}) \tag{8}$$

where N_{elect} represents the ranking of net electricity in the mesh concerned; P_{PV}, P_{WT}, and W_{mesh} represent the annual PV power generation, annual wind power generation, and annual electricity consumption by households and tertiary industries in each mesh, respectively. N_{elect} ranks regions with positive annual net electricity consumption to efficiently deploy RE and EVs in regions where renewable electricity can be utilized effectively.

3.5. Results

3.5.1. Regional Vehicle Analysis

Figure 7 shows the total number of private and company cars. The results indicated that a large number of potential introduction points were distributed in Mito, Tsukuba, and Hitachi, where the population was concentrated. In contrast, fewer vehicles were distributed in mountainous areas, such as the northern part of the prefecture and the northern part of Tsukuba. The number of households was used to estimate the distribution of passenger cars, while the number of offices was used for company cars. This approach resulted in the distribution of vehicles in population centers, where these factors are most prevalent. The mesh with the largest number of vehicles was located in Tsukuba, with an estimated 4689 vehicles per 1 km^2.

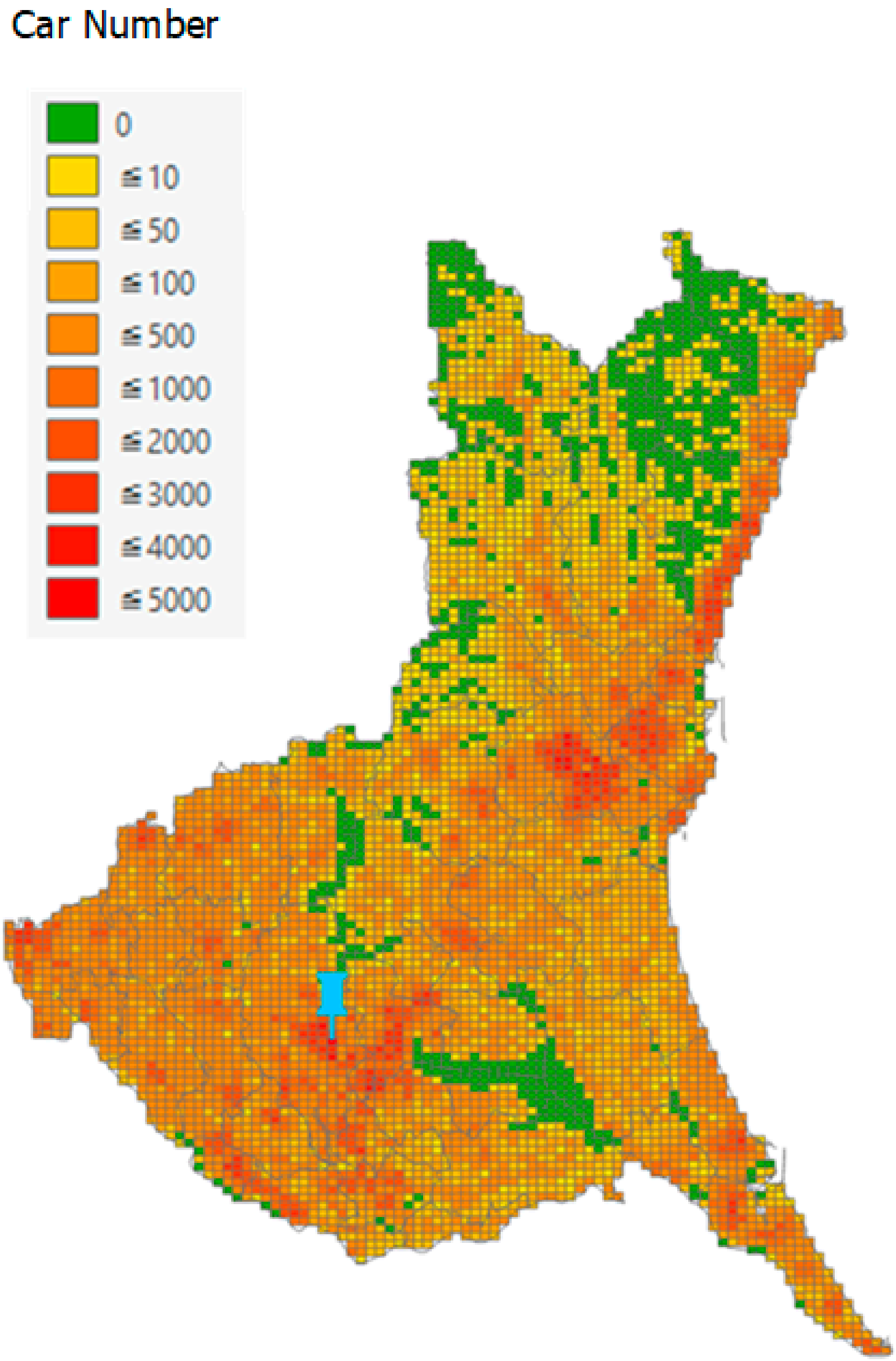


Figure 7. Private and company car distribution.

The taxi fleet was estimated by weighting the number of taxis around conventional train stations, resulting in a large number of taxis distributed around the terminal train station, as shown in Figure 8. However, stations in the northern and southeastern parts of the prefecture showed less potential for EV cab introduction, even near the stations. This is because the mesh population was used to calculate distributions. The mesh with the largest number of taxis was located in Toride, with an estimated 13.6 cabs per 1 km^2.

Buses tended to be distributed along bus routes, as shown in Figure 9. In addition, because the mesh along bus routes was divided by population, many buses were distributed in population centers, similar to private cars and company cars. The mesh with the largest number of buses was also located in Toride, where four buses were estimated per 1 km^2.

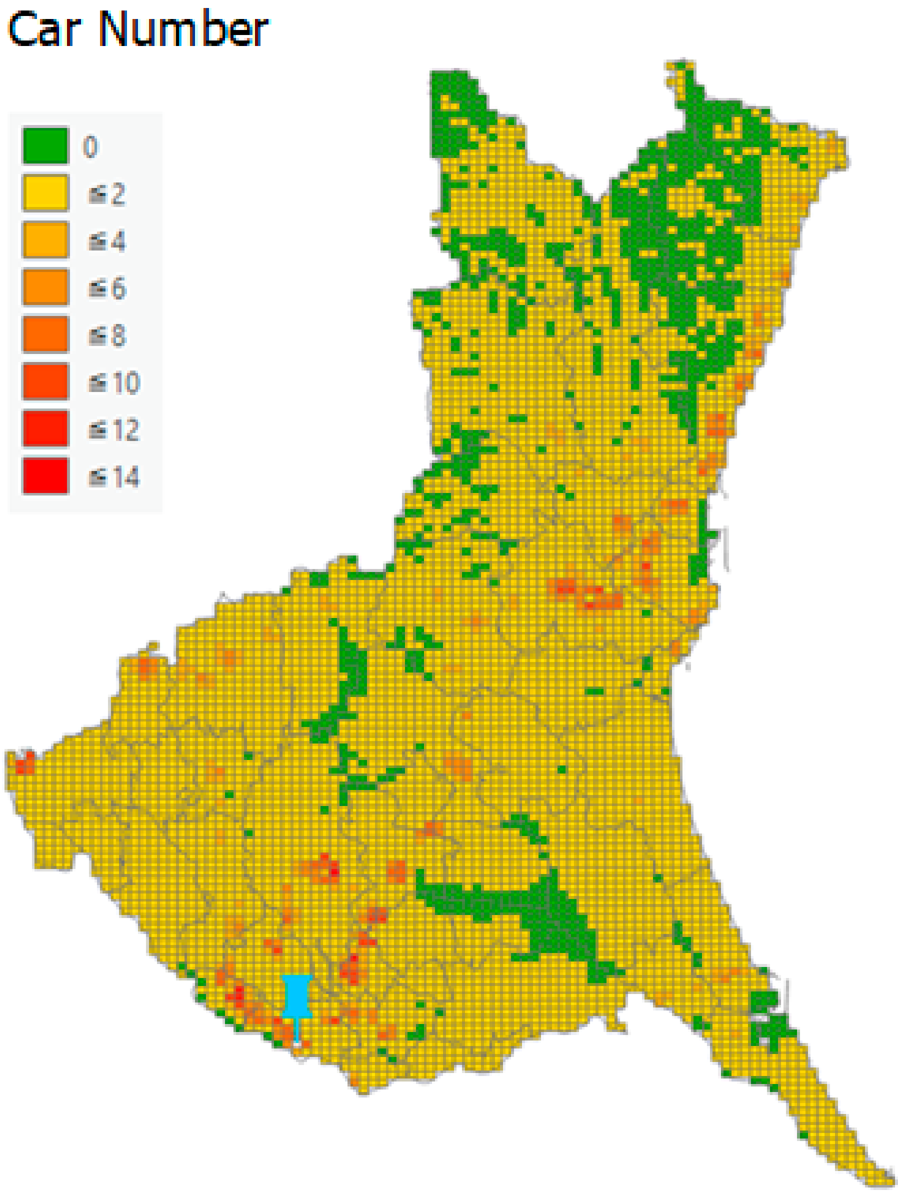


Figure 8. Taxi distribution.

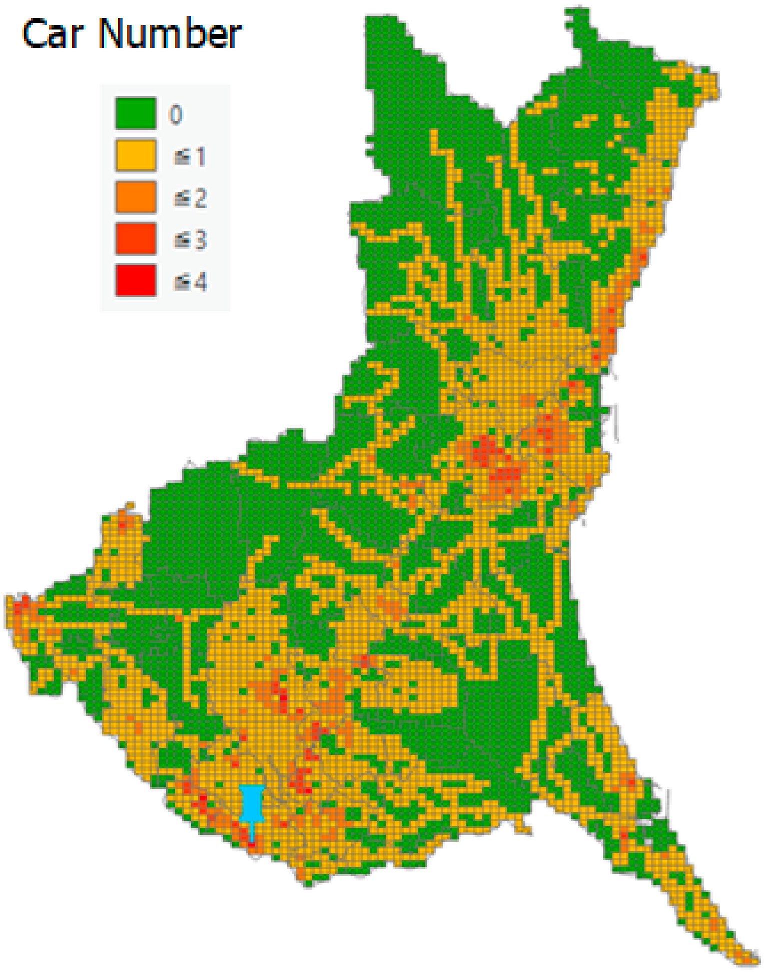


Figure 9. Bus distribution.

3.5.2. Regional RE and Demand Analysis

Figure 10 shows the distributions of PV and wind potential, and electric demand, in Ibaraki. PV potential is widely distributed in the prefecture. However, due to topographical constraints, there is less distribution around mountain areas. The location with the highest annual power generation potential is the mesh of Joso, which is expected to generate 43.7 GWh per year.

The distribution of wind power generation potential is opposite to that of solar power generation, with most wind power generation potential distributed in mountainous areas with abundant wind resources. The mesh of Kitaibaraki has the highest power generation potential and is expected to generate 39.2 GWh per year.

To use clean electricity derived from RE for EV driving and store surplus electricity, it is necessary to evaluate the overall electric demand in addition to the EV charging demand. Therefore, electric demand was calculated for each tertiary mesh, and the results are shown in Figure 10c. Similar to the distribution of vehicles, points with high electric demand were distributed mostly in populated areas. This is due to the same reason as for the number of vehicles: the population and the number of employees were used for proportional distribution. The mesh with the highest electric demand in the prefecture was located in Mito, with an estimated annual electric demand of 80.3 GWh.

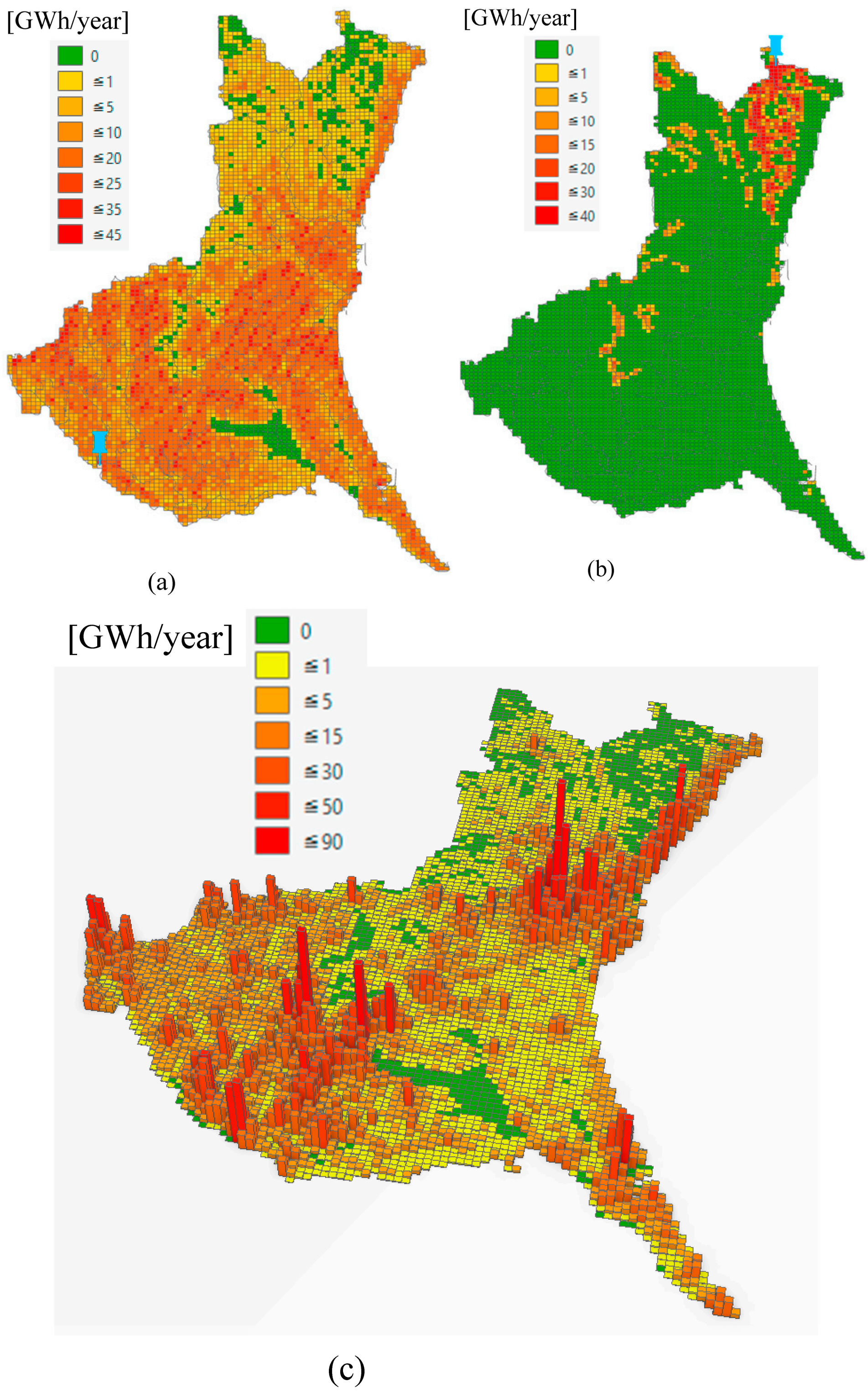


Figure 10. Regional distribution. (**a**) PV potential; (**b**) wind potential; (**c**) electric demand.

3.5.3. Results of Regional Evaluation and Discussion

This section provides the comparisons between Cases 1 and 2. Figure 11 shows a comparison of suitable locations for the combined use of RE and EVs. The results showed that in both cases, as mentioned above, the potential was concentrated in populated areas such as Mito, Hitachi, and Tsukuba. However, compared with Case 1, Case 2 showed a decrease in the number of upper meshes in cities such as Mito, Hitachi, and Toride. This can be attributed to the large population working in the tertiary industry, which reduces the number of suitable sites for RE and EVs when the electric demand of the tertiary industry is considered. Although Tsukuba also has a large population working in the tertiary industry, as mentioned above, the city covers a large area with many RE potentials distributed in areas that are generally considered rural, which may have increased the number of top meshes.

Figure 12 shows a comparison of suitable locations based on net electricity consumption and the combined use of RE and EVs. The results also show that in areas with abundant wind power potential in the northern part of the prefecture, such as Takahagi and Kitaibaraki, the net electricity generation is positive. However, these areas have few EVs to store the surplus electricity, resulting in a low potential when assessing the combined use of RE and EVs. On the other hand, areas such as Mito, Tsuchiura, and Koga show that although there are few areas with electricity surpluses, there are many areas with high potential because of the large number of EVs. Tsukuba has a large urban area with a large number of EVs and a rural area with high RE potential, resulting in substantial net electricity generation and suitable areas for combined use.

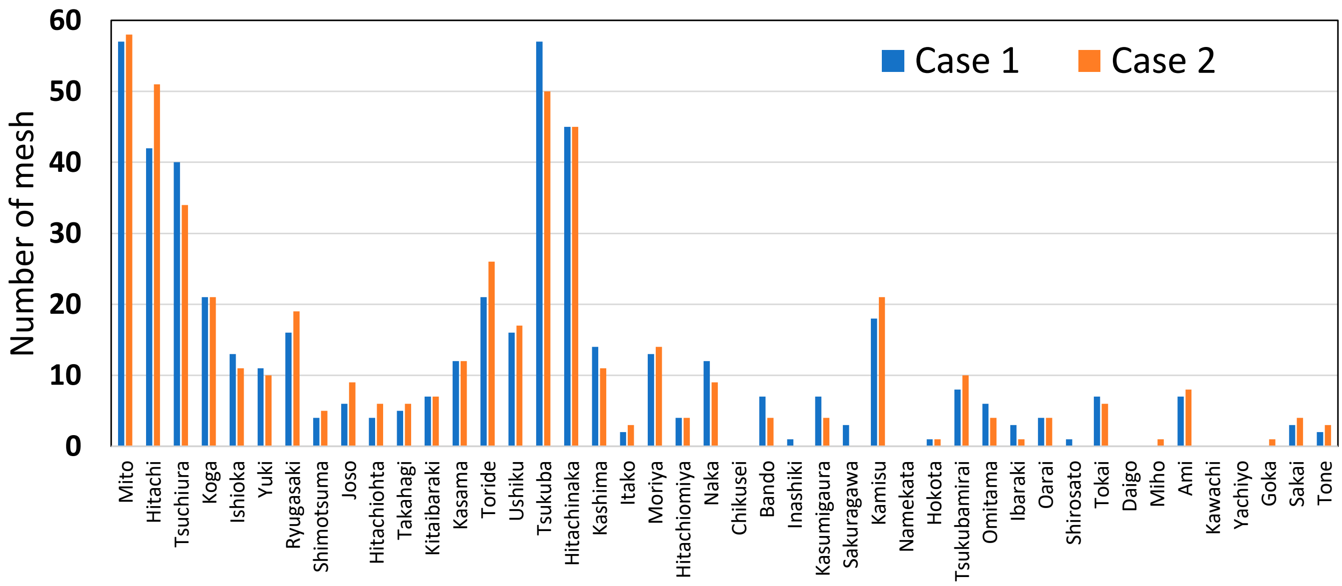


Figure 11. Comparison of suitable locations for combined use of renewable energy and electric vehicles.

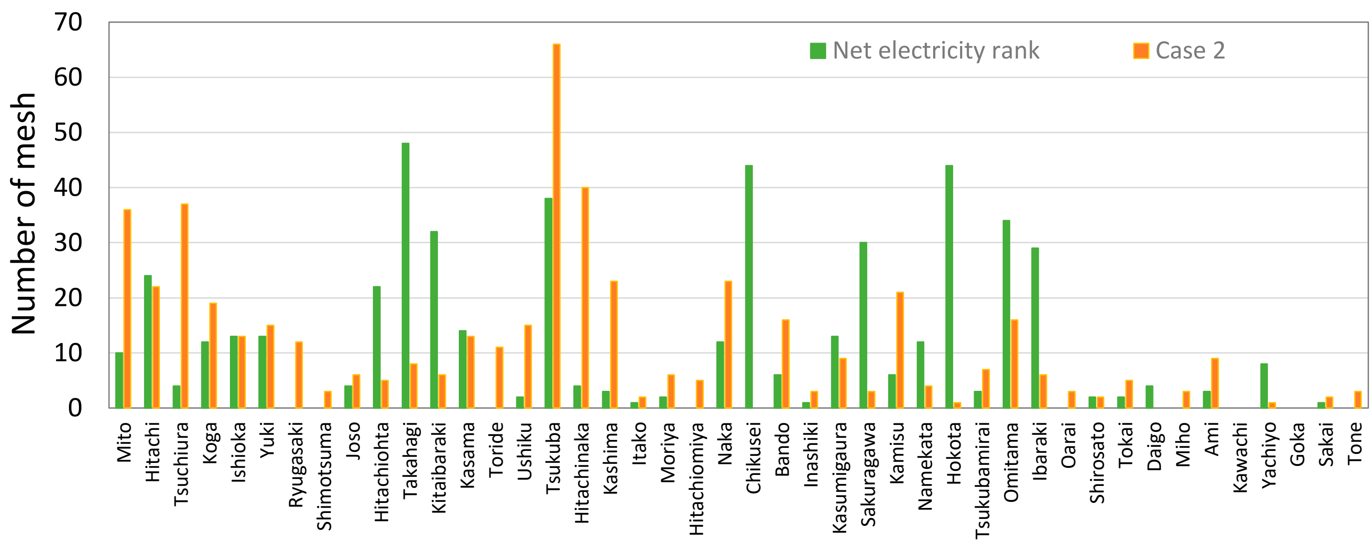


Figure 12. Comparison of suitable locations based on net electricity consumption and combined use of renewable energy and electric vehicles.

The detailed analysis of locations with high RE potential and low electric demand was conducted from the perspective of effective energy utilization. In terms of effective use, more RE and vehicles results in better outcomes. Therefore, using the average number of vehicles (232.8), the areas were classified as 'suitable locations' (red areas) and 'unsuitable locations' for effective energy use (green areas), as shown in Figure 13. The results show that effective use of energy can be expected in the meshes corresponding to the urban areas of Mito and Tsukuba. On the other hand, the meshes in Omitama, the northern part of the prefecture, Kasama, and Jori Town are not suitable for the use of RE and EVs due to high electric demand and a small number of EVs. Factories are mainly located in the meshes of these regions, suggesting the need to achieve net-zero energy in these areas using other methods.

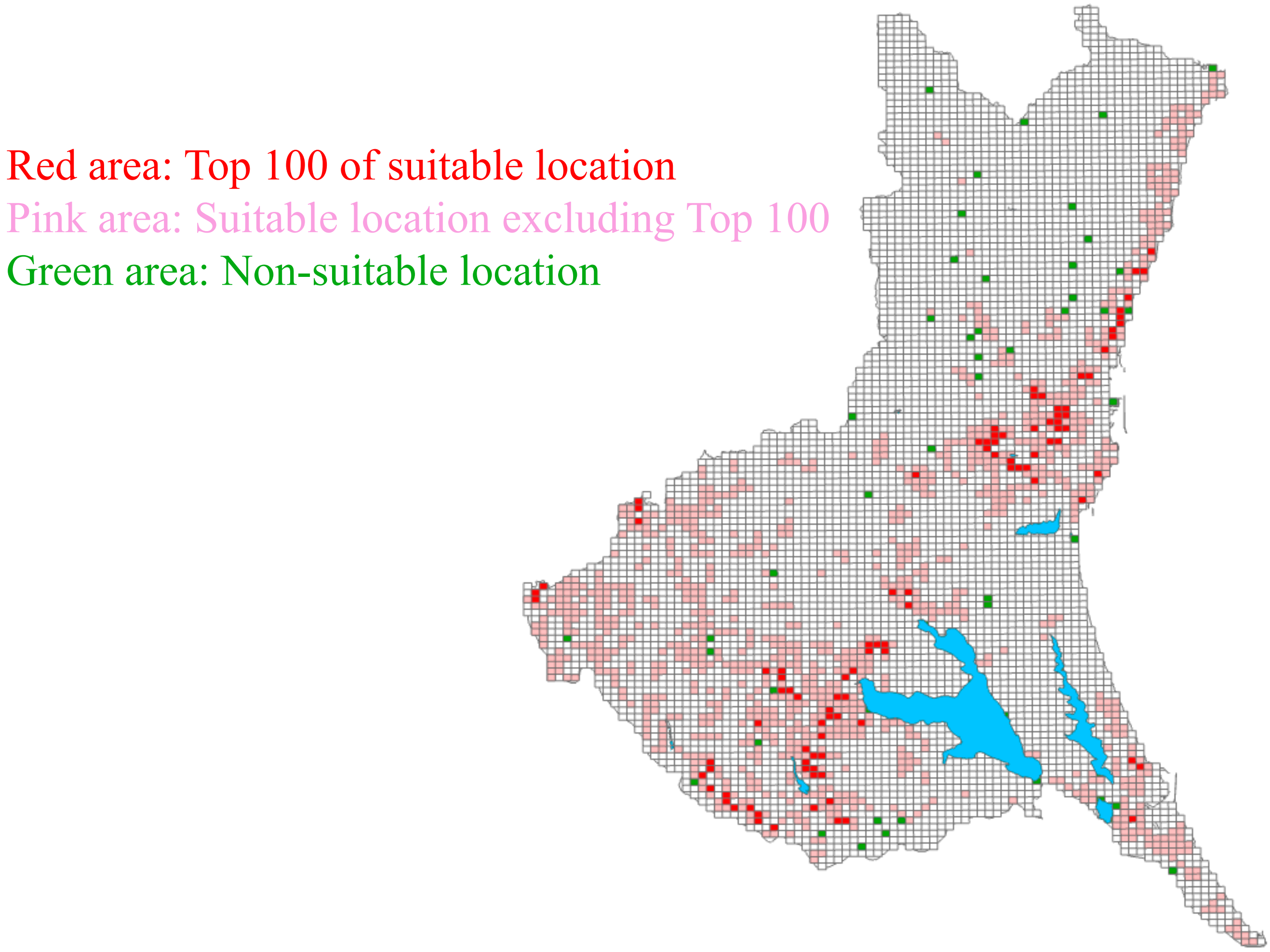


Figure 13. Distribution of suitable locations for combined RE and EV installation.

We evaluated the percentage of each rank in terms of PV potential, wind power potential, number of vehicles, number of buses, and number of taxis. The top meshes were almost equally balanced in influencing both the number of vehicles and RE potential. Additionally, the top meshes were predominantly distributed in urban areas and were not affected by wind power potential. A similar analysis was conducted for the medium-ranked meshes in terms of combined RE and EV potential. The results show that the elements of each indicator are sparsely represented compared with the top meshes. In Case 1, the number of buses, taxis, and solar potential were particularly influential; the absence or lack of these indicators likely resulted in a medium ranking. In Case 2, the ranking of net electricity had a significant impact, with some meshes, such as the Tsukuba mesh shown in the figure, showing very high net electricity and a strong impact, while others, such as Kamisu, had low net electricity and a strong impact of vehicles.

4. Conclusions

We conducted time-series and regional analyses in Japan to identify suitable areas for the mutual use of RE and EVs. A methodology was developed and examined to determine priority introduction points in Ibaraki Prefecture. This approach allows for assessing the national government's prioritization of prefectures and the prefectures' prioritization of municipalities based on their policies.

In the time-series evaluation, many prefectures achieved an in-prefecture self-sufficiency rate of 99% or higher, even in the case of maximum introduction. However, it is difficult to achieve a 100% self-sufficiency rate in urban areas, as the in-prefecture self-sufficiency rate is significantly affected by charging capacity. Therefore, while it is necessary to utilize vehicles, it is also important to shift peak demand by recharging RE through storage batteries and other resources. The study also indicated the importance of building an energy mix using other renewable energies and energy sources such as hydrogen.

Regional potential estimates were used to derive suitable sites for the combined use of RE and EVs under two different cases. A methodology encompassing the impacts of different dimensions of RE and EVs was studied and evaluated, and suitable locations for the combined use of RE and EVs were identified.

These evaluations provide a framework for the introduction and evaluation of RE and EV integration in Japan and contribute to policymaking for the mutual introduction of RE and EVs.

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