京都大学大学院経済学研究科
再生可能エネルギー経済学講座
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Empirical Study on Japan's Electricity Spot Market

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京都大学大学院経済研究科 **馬騰**
Teng Ma, Graduate School of Economics, Kyoto University
京都大学大学院経済研究科 再生可能エネルギー経済学講座 **杜依濛***
Yimeng Du (Corresponding author)**,** Research Project on Renewable Energy Economics, Kyoto University
国防科技大学前沿交叉学科学院 **徐涛**
Tao Xu, College of Advanced Interdisciplinary Studies, National University of Defense Technology
暨南大学経済学院 **陳旺**
Wang Chen, School of Economics, Jinan University

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Abstract:
This study examined the cross-regional impacts of renewable power generation in Tohoku on the electricity spot market in Tokyo. We use the hourly supply data of renewable power generation, cross-regional transmitted electricity, and transaction data in the electricity spot market to investigate how renewable power generated in a neigh- boring area affects the local spot price and market volatility. Our results indicate that the electricity spot market is affected not only by local renewable power generation, but also by renewable power generation in neighboring areas. The relatively higher price reduction effect of transmitted power is due to its higher price elasticity under a tight supply-demand balance. Specifically, our results confirm the cross-regional price stabilization impact of renewable power generation in Tohoku. The negative impact on realized volatility is due to the relatively more stable renewable electricity supply from Tohoku. Furthermore, we find that renewable power producers, especially solar power producers, are not incentivized by the fixed-price Feed-in Tariff to meet electricity demand during peak hours because of higher marginal costs.

Keywords: Spot Market; Renewable Electricity; Cross-regional effects; Japan

1. Introduction

The electricity spot market is one of Japan’s wholesale electricity markets, and diverse energy resources, including renewable energy, are traded on it. Along with deepening the reforms of marketization in Japan, renewable power suppliers are expected to play an important role in this market[1]. To generate a more competitive market, it is necessary to increase the penetration of renewable power, as this may reduce the wholesale spot prices. An increase in renewable power generation can displace marginal generation with high fuel costs (Rintama˙ki et al., 2017). In particular, since the marketization reform in April 2016, the trade volume in Japan’s electricity spot market has been increasing rapidly. Various electricity utilities have entered the market, stimulating competition and making it possible to trade renewable electricity directly with the suppliers in the market.

Renewable power plays an important role in the spot market. The existing literature on the effect of renewable energy power traded on the spot market suggests that the electric- ity spot market can benefit from increased solar and wind power generation in European countries and the US (Rintama˙ki et al., 2017; Martinez-Anido et al., 2016; Woo et al., 2011; Sensfuß et al., 2008; Paraschiv et al., 2014). Ma et al. (2019) examined the impact of renewable power supply on the electricity spot market in Japan and found that increasing renewable power generation reduces the spot price, and that stable renewable generation can reduce realized volatility.

Although regional power transactions in the Japanese spot market have been observed since the full liberalization of the electricity market in 2016, the impact of transmitted renewable power from neighboring regions on the local spot market remains unclear. To fill this research gap, this study examines the cross-regional impacts of renewable power generation on the Japan Electric Power eXchange (JEPX) spot market. Our objective is to examine the indirect impact of solar and wind power generation in Tohoku on the spot price and volatility in the electricity spot market of Tokyo. We limited the setting to Tokyo and Tohoku because of the complementary supply and demand relationship between these two areas. For example, Tohoku has huge renewable power potential but less power demand, while Tokyo has more power demand (Wakiyama and Kuriyama, 2018). Simultaneously, the “Tokyo–Tohoku electricity grid” is relatively isolated from other areas of Japan. The country is divided between Tokyo and Chubu by different mains frequency and between Hokkaido and Tohoku by geographical isolation (Figure 1).

[Figure 1]

This study makes the following contributions to the existing literature. First, in contrast to the

[1] The system reforms on electricity market in Japan were implemented by Ministry of Economy, Trade and Industry (METI) since 1995.

results of Ma et al. (2019), we found that the electricity spot market is not only affected by local renewable power generation, but also by renewable power generation in the neighboring areas. Further, the power generation in Tohoku has higher price reduction effects compared to the local renewable generation since the cross-regional power from Tohoku is used to address electricity shortages in Tokyo. In general, power transmitted to fill an electricity demand gap has higher price elasticity; thus, it has higher price reduction effects. Second, we estimated the impacts of renewable power production in neighboring areas on the realized volatility of the local electricity market. The result shows that the negative impacts on realized volatility may be caused by the relatively stable renewable electricity supply from Tohoku. However, the current transmission capacities between Tohoku and Tokyo are insufficient to support the transmission load (Wakiyama and Kuriyama, 2018). We suggest that further improvement in the capacity of the interconnection grid can reduce and stabilize the spot prices. Finally, this study investigated whether the impact of transmitted renewable power on the local electricity market varies with changes in the local electricity demand. The results reveal a higher price stabilization impact in the off-peak period since power producers tend to avoid higher marginal costs during peak periods. This result suggests that renewable power producers are not incentivized to supply more electricity in response to increasing electricity demand. The Feed-in Tariff (FIT) scheme does not provide an incentive for power producers under the market base due to the fixed price.

The remainder of this study is organized as follows. Section 2 presents an overview of the transactions on the JEPX in Tokyo and the combination of power sources and renewable electricity in Tohoku and Tokyo. In Section 3, we describe the empirical methodology and data used in the analyses. The estimation results are presented and discussed in Section 4. Finally, Section 5 presents our conclusions and the implications of this research.

2. Background

The electricity spot market was established in Japan to enable new power retailers to supply power at low prices, as part of reforms designed to foster competition in the market[2]. However, owing to the inadequate transfer capabilities for cross-border transmission, the spot prices in the JEPX are set at different levels for various service regions (Figure 2). A relatively higher price level is observed in the eastern grid, which includes the regions of Hokkaido, Tohoku, and Tokyo, due to the unbalanced electricity supply and demand in this area. Conversely, the areas in the western grid show consistent price levels due to their relatively sufficient cross-regional electricity transmission. Meanwhile, the lower deviation of the spot price in Tokyo implies a

[2] The electricity spot market was established by JEPX in 2005 to ensure fair competition in Japan's wholesale electricity market. The spot market is the primary market of the JEPX. Approximately 96.3% of the electricity trades during the fiscal year (FY) 2018 occurred in the spot market. We calculated this share by dividing the trading value of the spot market by the total trading value of the JEPX in 2018 (JEPX, n.d.).

more liberalized market.

[Figure 2]

As an "absolute clean energy", renewable power is also transacted in the electricity market; however, only about 1% of the total electricity transactions in the JEPX in 2015 were related to renewable power (METI, 2016). To enhance the proportion of renewable power transactions in the JEPX, the Japanese government has made efforts to promote renewable power, especially after the Fukushima nuclear accident in March 2011. As the main policy instrument, the FIT scheme was introduced in July 2012 to replace the Renewable Portfolio Standards system that had been in force since April 2003 (Sakabe et al., 2020). Moreover, an "Energy Mix" target for FY2030 was announced by the Japanese government in July 2015, which aimed to increase the share of renewable energy in Japan's total power generation from 14.5% in 2016 to 22–24% by 2030 (METI, 2015).

Although the tariff rate under the FIT has continued to decrease in recent years, solar power generation has increased from 66,133 GWh in 2012 to 626,677 GWh in 2018 (METI, 2019). Meanwhile, renewable power production also displays regional trends. As shown in Figure 3, solar power generation is higher in Tokyo, Chubu, and Kyushu, whereas wind power generation is more prominent in Hokkaido, Tohoku, and Tokyo.

[Figure 3]

We selected Tokyo and Tohoku as the setting for this study due to the special nature of the electricity grid in Japan (Figure 1). The country is divided into two parts, each at a different mains frequency. The eastern grids (including Hokkaido, Tohoku, Tokyo, and the eastern part of Chubu) and western grids (including Chubu, Kansai, Chugoku, Shikoku, and a major area of Kyushu) are connected by high-voltage direct current connections. The frequency is 50 Hz and 60 Hz in the eastern and western grids, respectively.

In the eastern grid, there is limited transmission capacity between Hokkaido and Tohoku due to the geographic location of Hokkaido, which is isolated from the Japanese mainland. The Tohoku–Tokyo line is the busiest connection in Japan, as Tokyo accounts for nearly 37% of Japan's electricity consumption (OCCTO, 2020). Approximately 27,575 GWh electricity was transmitted from Tohoku to Tokyo in FY 2019 (Table 1)[3]. Despite efforts to increase the capacity of interconnection lines among areas, there is frequent disconnection between the spot markets, especially between Hokkaido–Honshu and Tokyo–Chubu[4]. Specifically, during the first quarter of 2019, the average occurrence rate of spot market disconnection between

[3] The transmission values were calculated by the sum of forward transmission and counter transmission on the interconnection lines.

[4] The largest and most populous main island of Japan. The region include all areas in Japan excepting Hokkaido, Kyushu and Okinawa.

Hokkaido and Honshu was 94.5%, and that between Tokyo and Chubu even reached 99% (METI, 2020a). During FY 2019, the annual magnitudes of transmitted electricity on the cross-regional lines of Hokkaido–Honshu and Tokyo–Chubu were only 2,396 GWh and 4,501 GWh, respectively. Therefore, the electricity grid in the "Tohoku–Tokyo" area considered in this study is relatively isolated from the other areas in Japan. For this reason, we focus on these areas to study the cross-regional impacts of renewable power generation on the electricity market. The higher solar and wind power generation in Tokyo is because of the higher electricity demand there, whereas the higher wind power production in Tohoku and Hokkaido is a result of these areas' superior wind resources (Mizuno, 2014).

[Table 1]

3. Methodology and Data

3.1. Empirical model

A traditional two-stage least-squares (2SLS) framework was used to examine the cross-regional impact of Tohoku's renewable power generation on the Tokyo spot market. To consider the partial autocorrelations in the spot price, realized volatility, and electricity transmission, we used the autocorrelation distributed log model in both stages of the model. Furthermore, both the renewable generation and electricity transmission were considered exogenous to the spot price and realized volatility, since the spot price is decided after the bidding in the electricity spot market. The first stage of the 2SLS model predicts the direct effects of Tohoku's renewable power generation on the transmission of electricity from Tohoku to Tokyo.

$$Transmission_t = \beta_0 + \beta_1 lag\ transmission_t + \beta_2 Re(Tohoku)_t + \beta_3 Control_t + \varepsilon_t, \quad (1)$$

where $Transmission_t$ i is the dependent variable and refers to the electricity transmitted from Tohoku to Tokyo in hour t. This net electricity transmission from Tohoku to Tokyo was calculated by subtracting Transmission (Hokkaido Forward) from Transmission (Tohoku Forward), owing to the almost zero electricity transmission from Tokyo to Tohoku. $lag\ Transmission_t$ shows the lagged terms of the transmitted electricity generations, which includes $lag(1hour)Transmission_t$, $lag(1day)Transmission_t$, and $lag(1week)Transmission_t$ for separately considering the short run dynamic terms by one hour before, one day before, and one week before. $Re(Tohoku)_t$ represents the renewable power generation, including the solar and wind power sectors in Tohoku ($Solar(Tohoku)_t$ and $Wind(Tohoku)t$, respectively). $Control_t$ includes control variables indicating other factors that may affect the electricity transmission from Tohoku to Tokyo, including $Forecast(Tohoku)_t$, $Forecast(Tokyo)_t$, and $Primary(Tohoku)_t$. $Forecast(Tohoku)_t$, $Forecast(Tokyo)_t$ are the first differences of hourly electricity demand forecast in Tohoku and Tokyo, used to represent the expected demand on electricity[5]. *Primary(Tohoku)$_t$* is the share of primary energy generation in Tohoku, including thermal, hydroelectric, and nuclear power[6]. ε_t is the error term.

The second stage estimates the cross-regional impact of Tohoku's renewable power generation on the spot price in Tokyo through its impact on electricity transmission between the two regions.

$$\mathrm{Price_t} = \gamma_0 + \gamma_1 \mathrm{lag}\, Price_t + \gamma_2 Re(Tokyo)_t + \gamma_3 \widehat{Transmission}_t + \gamma_4 Control_t + \varepsilon_t, \quad (2)$$

where *Price$_t$* is the dependent variable for stage 2 that represents spot price in hour *t*. *lag Price$_t$* is denoted as the lagged terms of the spot prices, including the price 1 hour before $lag(1\,hour)Price_t$, 1 day before $lag(1day)Price_t$, and 1 week before $lag(1week)Price_t$. $Re(Tokyo)_t$ represents the renewable power generation, including the solar and wind power sectors in Tohoku ($Solar(Tokyo)_t$ and $Wind(Tokyo)_t$, respectively). $\widehat{Transmission}_t$ is the value of $Transmission_t$ predicted by equition (1), represents the cross-regional impacts of Tohoku's renewable power generation in Tokyo through the interconnection line between Tohoku and Tokyo in hour t. $\widehat{Transmission}(Solar)_t$ is used to represent the predicted value of the impacts of Tohoku's solar power generation on transmission generation, and $\widehat{Transmission}(Wind)_t$ is for that of wind power. $Control_t$ includes control variables indicating other factors that may affect the electricity transmission from Tohoku to Tokyo, including FIT_t, $TransImpact_t$, $Primary(Tokyo)_t$, and $Forecast(Tokyo)_t$. FIT_t represents the tariff rates provided for solar power under the FIT[7]. $TransImpact_t$ represents the other indirect impacts on Tokyo through by the cross-regional interconnection line between Tohoku and Tokyo in hour \$t\$, except the renewable power generation. $Primary(Tokyo)_t$ is the share of primary energy generation in Tokyo. By using the log-log specification equation, our results imply that the estimated coefficient of the logarithmic renewable power generation and other variables represent the elasticity of the day-head spot price on the JEPX, while $Primary(Tohoku)_t$ and $Primary(Tokyo)_t$ are not converted to logarithmic form due to their special nature.

We also focused on the impacts of renewable power generation on realized volatility. Market volatility can be explained by the liquidity provision process and reflects market activity and the security risks (Chordia et al., 2002; Copeland and Galai, 1983; Tauchen and Pitts, 1983). In this study, daily realized volatility was considered as market activity, which was calculated as the sum of squared hourly price changes (Andersen et al., 2003). It was defined by the following

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[5] First differences were selected due to the Augmented Dickey-Fuller (ADF) unit roots test indicating that the series is unstationary for hourly electricity demand forecast in Tohoku and Tokyo.

[6] The share is calculated by the sum of the generation of baseload supply and mid-range load supply divided by electricity demand.

[7] The tariff rate for solar power is used to represent the overall tariff rate, due to overcome the multicollinearity in our measure.

equations:

$$Return_t = ln\left(\frac{P_t}{P_{t-1}}\right), \tag{3}$$

$$RV_d = \sqrt{\left(\sum_{t=1}^{24} Return_t^2\right)}\ . \tag{4}$$

where Pt illustrates the hourly transaction price in day ahead spot market on hour t, $Return_t$ represents the hourly change of spot price, which is calculated by taking the natural log of the quotient of the spot price on hour t divided by the price an hour before. RV_d is the realized price volatility on day d.

Therefore, the first stage of our 2SLS model predicts the direct effects of Tohoku's renewable power generation on electricity transmission from Tohoku to Tokyo on a daily basis. The model to analyze the effect of realized volatility can be described as follows:

$$Transmission_d = \beta_0 + \beta_1 lagTransmission_d + \beta_2 Re(Tohoku)_d + \beta_3 Control_d + \varepsilon_{d,} \tag{5}$$

The second stage estimates the cross-regional impact of Tohoku's renewable power generation on realized volatility through its impact on electricity transmission between the two regions.

$$RV_d = \gamma_0 + \gamma_1 lagRV_d + \gamma_2 Re(Tokyo)_d + \gamma_3 \widehat{Transmission}_d + \gamma_4 Control_d + \varepsilon_d, \tag{6}$$

where RV_d is the dependent variable for stage 2; it represents realized volatility on day d in the Tokyo electricity spot market. The lagged terms $lagIndicator_d$ contain the realized volatility 1 day before (RV_{d-1}) and 1 week before (RV_{d-7}), indicating the dynamic process. The other independent variables were converted from hourly to daily data, and ε_{im} is the error term.

3.2. Data

All samples were collected from April 1, 2016, to March 31, 2020. Tokyo's spot price data were obtained from the homepage of the JEPX website. Since the spot price is calculated for 48 products traded in 30-minute time intervals on the day before, the hourly price data were calculated based on the mean of each of the two time interval values in 1 hour (JEPX, n.d.[b]). The energy generation data were acquired from the electric power companies in Tohoku and Tokyo, covering various electricity sources such as nuclear, thermal, inflow- type hydroelectric, geothermal, biomass, solar, wind, and pump-storage-type hydroelectric; moreover, regional power transmission was calculated based on the cross-regional interconnected lines (Tohoku EPCO, Tokyo EPCO, and Hokkaido EPCO). The tariff rates of FIT were obtained from the

Agency for National Resources and Energy (ANRE, n.d.[a]). We also gathered the electricity demand forecast datasets from the Organization for Cross-regional Coordination of Transmission Operator, Japan (OCCTO, n.d.).

Descriptive statistics are shown in Table 2. Panel A presents the summary of the hourly dataset. The sample included all trading hours from April 2016 to March 2020 for Tohoku and Tokyo, with 35,064 observations for each variable. The average Tokyo spot price was 9.818 Yen/kWh. The average hourly solar and wind power generation was 1,603 MWh and 106.9 MWh in Tokyo and 575.8 MWh and 277.8 MWh in Tohoku, respectively. As Figures 4 and 5 show, the spot price is relatively stable, with strong intraday and annual seasonal patterns in Tokyo. The price was observed to be higher during the daytime, except for the lunch break, and in the spring and summer seasons each year, suggesting that higher electricity demand occurs during the afternoon, and in spring and summer. The realized volatility also was higher in summer and winter; however, it has become more stable in recent years, indicating more frequent transactions (Figure 6). As shown in Figures 7–10, the supply of solar and wind power shows intraday and seasonal patterns every year. The supply generated from solar power was higher in Tokyo, while that from wind power was lower. Meanwhile, the average electricity transmission from Tohoku to Tokyo was 2,544 MWh. Figures 11 and 12 represent the hourly and monthly trends in the electricity transmission from Tohoku to Tokyo, respectively. The transmission increased gradually, displaying strong intraday and annual seasonal patterns. Panel B of Table 2 summarizes the daily dataset. The sample included the trading days during the study period for Tohoku and Tokyo, with 1,461 observations for each variable. The daily electricity generation data, electricity demand forecast data, and gross regional transmission data were calculated by adding the hourly intraday data. The average realized volatility in Tokyo was 0.435% during the whole sample period, while the realized volatility was almost always higher than 2% in February and August (Figure 6).

[Table 2]

[Figures 4-12]

4. Results

4.1 Spot price

Table 3 reports the impacts of renewable power generation in Tohoku on the electricity transmission from Tohoku to Tokyo based on equation (1). Column (1) lists the baseline estimations by eliminating the control variables $Control_t$. The estimates with the control variables $Control_t$ are reported in columns (2) and (3); column (3) includes the hourly, monthly, and yearly dummy variables.

[Table 3]

All the coefficients of the lagged terms (*lagTransmission*$_t$) are positive and statistically significant in all columns of Table 3, suggesting that the electricity transmission in any period strongly depends on the electricity transmission in preceding periods. *Solar(Tohoku)*$_t$ and *Wind(Tohoku)*$_t$ are positive and statistically significant in columns (2)–(3), which means that increasing renewable power generation in Tohoku also increases the electricity transmission from Tohoku to Tokyo. In particular, the coefficient is 0.011 for *Solar(Tohoku)*$_t$ and 0.006 for *Wind(Tohoku)*$_t$ in column (3), suggesting that a 1% increase in solar and wind power generation leads to a 0.011% and 0.006% increase in electricity transmission, respectively. The coefficients of *Primary(Tohoku)*$_t$ are positive and statistically significant in columns (2) and (3), meaning that the base-load and mid-range energy resources lead to an increase in electricity transmission. *D_Forecast(Tohoku)*$_t$ and *D_Forecast(Tokyo)*$_t$ have opposite and statistically significant signs, suggesting that higher electricity demand plays an important role in electricity transmission[8]. These findings indicate that renewable power was transmitted from Tohoku to Tokyo to deal with the unbalanced electricity demand and supply situation in Tokyo.

Along with increasing renewable power generation in Tohoku, the cross-regional transmission of renewable power also increased. However, the relatively low coefficients of *Solar(Tohoku)*$_t$ and *Wind(Tohoku)*$_t$ suggest that only a small share of renewable power can be transmitted through the Tohoku–Tokyo interconnection line. This result indicates the need for reinforcement of the interconnection line to increase transmission capacity and capability on responding to variable renewable energy generation.

The regression results on the impacts of renewable power generation on the electricity spot market in Tokyo are presented in Table 4. The results listed in column (1) are based on the model that only focuses on local power generation. Column (2) reports the results after adding transmitted power from Tohoku. The estimation results with control variables *Control*$_t$ and interaction terms *Interaction*$_t$ are shown in columns (3)–(5).

[Table 4]

All the lagged terms of spot price $lagPrice_t$ have positive and statistically significant coefficients in all columns, which means that the spot price in Tokyo's electricity spot market can also be determined by the previous prices. Both the $Solar(Tokyo)_t$ and $Wind(Tokyo)_t$ coefficients are negative and statistically significant, suggesting that increasing local renewable power generation helps to reduce the spot price in the Tokyo's market. For example, the coefficient is -0.006 for $Solar(Tokyo)_t$ and -0.002 for $Wind(Tokyo)_t$ in column (3),

8 $D\_Forecast(Tohoku)_t$ and $D\_Forecast(Tokyo)_t$ represent the first-order difference terms of $Forecast(Tohoku)_t$ and $Forecast(Tokyo)_t$ because the null hypothesis was not rejected by the ADF unit root test, indicating that the series was not stationary for these variables.

suggesting that a 1% increase in local solar and wind power generation leads to a 0.006% and 0.002% decline in spot price, respectively. The findings are consistent with the results of Ma et al., (2019), who report that a 1% solar and wind power generation leads to a 0.014% and 0.001% reduction in the spot price for the entire country. $\widehat{Transmission}(Solar)_t$ and $\widehat{Transmission}(Wind)_t$ are negative and statistically significant in columns (2) and (3), which means that increasing renewable power generation in Tohoku can also help reduce the electricity spot price in Tokyo's spot market. The results suggest that a 1% increase in the cross-regional impacts of solar and wind power generation in Tohoku induces a 0.013% and 0.003% decline, respectively, in Tokyo's spot price[9]. These results confirm the existence of cross-regional impacts of Tohoku's renewable power on Tokyo's spot market. The cross-regional impact of solar power generation was higher than that of wind power generation, as there is lower generation of wind power compared to solar power in Tohoku (Figure 3). FIT_t is negative and statistically significant in columns (3)— (5), which suggests that the introduction of the FIT system has significantly reduced the spot price in Tokyo's spot market. This may be because the FIT scheme sufficiently encourages the promotion and market participation of renewable power in Tokyo. Our results contrast with Böhringer et al. (2017) which focused on Germany electricity market indicates that the feed-in tariffs increase the average household electricity price in Germany. We consider that it is due to the lower renewable generation in Japan that compare with Germany. *Primary(Tokyo)$_t$* had a positive and statistically significant coefficient, which means that the base-load and mid- range energy resources can lead to an increase in Tokyo's electricity spot price because of the higher marginal cost of base-load energy sources compared to renewable energy (Antweiler and Muesgens, 2021).

Moreover, to investigate whether the price reduction impact of renewable power generation can be differed by differences in electricity demand, the interaction terms of $\widehat{Transmission}_t$ and period dummy variables $Period_t$ are added to Equation (2) as follows:

$$Price_t = \gamma_0 + \gamma_1 lagPrice_t + \gamma_2 ReTokyo_t + \gamma_3 \widehat{Transmission}_t + \gamma_4 Control_t + \gamma_5 Period_t + \gamma_5 Period_t \times \widehat{Transmission}_t + \varepsilon_t, \quad (7)$$

$Period_t$ including dummy variables $Peak_t$ and $Daytime_t$, where $Peak_t$ indicates the peak period of electricity demand in spot market, that equal to 1 during 1:00 p.m. -- 4:00 p.m, and 0 otherwise. $Daytime_t$ is used to represent the daytime of a day. The variable equals to 1 during 8:00 a.m. -10:00 p.m, and 0 otherwise. The summarization of coefficients γ_3 and γ_5

[9] The coefficients of the indirect impacts of Tohoku's renewable power generations were calculated by the products of the coefficients of $Re(Tohoku)_t$ ($Solar(Tohoku)_t$ and $Wind(Tohoku)_t$) and the coefficients of $\widehat{Transmission}_t$ ($\widehat{Transmission}(Solar)_t$ and $\widehat{Transmission}(Wind)_t$). For example, the coefficients of the indirect impacts of Tohoku's solar power generation was calculated by product of the coefficients of $Solar(Tohoku)_t$ and $\widehat{Transmission}(Solar)_t$: 0.011 × -1.226 that equal -0.013, and the coefficients of the indirect impacts of Tohoku's wind power generation was calculated by product of the coefficients of $Wind(Tohoku)_t$ and $\widehat{Transmission}(Wind)_t$: 0.006 × -0.472 that equal -0.003.

represents the cross-regional impact of Tohoku's renewable power generation on spot price during the peaktime/daytime, and γ_3 shows the impact during the off-peak/nighttime.

The estimation results are presented in columns (4) and (5) of Table 4. The coefficients of $Peak_t$ and $Daytime_t$ are positive and statistically significant, which suggests that the spot price was higher in periods with higher electricity demand. $\widehat{Transmission}(Solar)_t$ is negative and statistically significant. By contrast, the cross-term $Peak_t \times \widehat{Transmission}(Solar)_t$ positive and statistically significant in column (4), which suggests that the cross-regional price reduction impacts of Tohoku's solar power generation were higher during the off-peak periods.

By contrast, both $\widehat{Transmission}(Wind)_t$ and $Peak_t \times \widehat{Transmission}(Wind)_t$ are negative and statistically significantly correlated with the spot price, meaning that the impacts on the spot price of transmitted wind power were notable during the peak period. The coefficients indicate that a 1% increase in the solar and wind power generation in Tohoku induces about a 0.0008% and 0.009% reduction, respectively, in the spot price during peak time. During the off-peak time, the price reduction impact of transmitted solar and wind power generation is 0.014% and 0.002%, respectively[10].

From the daytime sub-sample, we find that the coefficients of $\widehat{Transmission}(Solar)_t$ and the cross-term $Daytime_t \times \widehat{Transmission}(Solar)_t$ are negative and statistically significant in column (5), meaning that the cross-regional price reduction impacts of solar power generation w ere higher during daytime. Meanwhile, coefficients of $\widehat{Transmission}(Wind)_t$ and the cross-terms $Daytime_t \times \widehat{Transmission}(Wind)_t$ show opposite sign in column (5), suggesting that the cross-regional impacts of Tohoku's wind power generation were higher during the nighttime. For example, a 1% increase in Tohoku's solar and wind power generations induces a 0.017% and 0.007% reduction, respectively, in the spot price during daytime. The cross regional price reduction impact during nighttime of solar power is 0.010% and that of wind power is 0.004%[11].

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[10] The coefficients of the indirect impacts of Tohoku's solar power generation during peak time period was calculated by product of the coefficients of $Solar(Tohoku)_t$ and ($\widehat{Transmission}(Solar)_t$ + $Peak_t \times \widehat{Transmission}(Solar)_t$): 0.011 × (-1.316+1.242) = -0.0008, and the coefficients of the indirect impacts of Tohoku's wind power generation during same period was calculated by product of the coefficients of $Wind(Tohoku)_t$ and ($\widehat{Transmission}(Wind)_t$ + $Peak_t \times \widehat{Transmission}(Solar)_t$): 0.006 × (-0.339-1.092) = -0.009. Meanwhile, the coefficients of the indirect impacts of Tohoku's solar power generation during off-peak time period was calculated by product of the coefficients of $Solar(Tohoku)_t$ and $\widehat{Transmission}(Solar)_t$: 0.011 × -1.316 = -0.014, and the coefficients of the indirect impacts of Tohoku's wind power generation during same period was calculated by product of the coefficients of $Wind(Tohoku)_t$ and $\widehat{Transmission}(Wind)_t$: 0.006 × -0.339 = -0.002.

[11] The coefficients of the indirect impacts of Tohoku's solar power generation during daytime period was calculated by product of the coefficients of $Solar(Tohoku)_t$ and ($\widehat{Transmission}(Solar)_t$ + $Daytime_t \times \widehat{Transmission}(Solar)_t$): 0.011 × (-0.933-0.587) = -0.017, and the coefficients of the indirect impacts of Tohoku's wind power generation during same period was calculated by product of the coefficients of $Wind(Tohoku)_t$ and ($\widehat{Transmission}(Wind)_t$ + $Daytime_t \times \widehat{Transmission}(Solar)_t$): 0.006 × (674-1.847) = -0.007. The coefficients of the indirect impacts of Tohoku's solar power generation during nighttime period was calculated by product of the coefficients of $Solar(Tohoku)_t$ and $\widehat{Transmission}(Solar)_t$: 0.011 × -0.933 = -0.010, and the coefficients of the indirect impacts of Tohoku's wind power generation during same period was calculated by product of the coefficients of $Wind(Tohoku)_t$ and $\widehat{Transmission}(Wind)_t$: 0.006 × 0.674 = 0.004.

In summary, the estimation results of the second stage model suggest that both the local renewable power generation and the renewable power transmitted from Tohoku via the cross-regional interconnection lines can help reduce the electricity spot price in Tokyo. Higher price reduction impacts were observed for the transmitted power. We consider that this is due to the electricity transmission from a neighboring area, which helped address the electricity shortage in the local market. The transmitted renewable power has a relatively higher price elasticity, further increasing the price reduction impact.

Moreover, the results indicate that the cross-regional price reduction impact of wind power generation was higher that of solar power generation during peak time, while opposite impacts were found during off-peak time. We interpret this to mean that the wind power suppliers in Tohoku are more actively providing electricity to match higher demand, and thus, induce a higher price reduction impact during peak times (Figure 10). Further, although Tohoku has tremendous wind power resources, the share of wind power generation in the electricity demand of the area is still relatively small[12], Such insufficient power generation leads to a comparatively small impact on price reduction. Meanwhile, the cross-regional price reduction impact of solar power is higher during off-peak time. We consider this to be a result of solar power suppliers' behaviors; they tend to avoid trading during peak time owing to the higher marginal costs.

4.2 Realized Volatility

We also investigated the impact of Tohoku's renewable power generation on realized volatility in Tokyo's electricity spot market. The 2SLS framework was used to estimate the cross-regional impacts on realized volatility in the JEPX, using the same procedure as before. The regression results for the impacts of Tohoku's renewable power generation on the electricity transmission from Tohoku to Tokyo are presented in Table 5. The structure of Table 5 is the same as in Table 3.

[Table 5]

All the coefficients of the lagged terms of $Transmission_d$ are positive and statistically significant in all columns of Table 3. The daily transmitted electricity is strongly dependent on previous electricity transmission. $Solar(Tohoku)_d$ and $Wind(Tohoku)_d$ are positive and statistically significant in columns (2) are (3), which means that increasing the renewable power generation in Tohoku leads to an increase in the electricity trans- mission from Tohoku to Tokyo. In particular, the coefficient is 0.080 for $Solar(Tohoku)_d$ and 0.032 for $Wind(Tohoku)_d$ in column (3), which suggests that a 1% increase in daily solar and wind power generation leads to a 0.080% and 0.032% increase in electricity transmission, respectively. The coefficients $Primary(Tohoku)_d$, $D\_Forecast(Tohoku)_d$ and $D\_Forecast(Tokyo)_d$ are similar to

[12] The share was 3.481% during peak time and 3.523% during off-peak time.

the results in Table 3, demonstrating the consistency of the hourly and daily estimations. The regression results for the second stage model based on equation (4) illustrate the impacts of renewable power generation on the realized volatility (Table 6). In contrast to column (3), the results for the estimation without controls are listed in columns (1) and (2).

[Table 6]

All the lagged terms of realized volatility RV_d have positive and statistically significant coefficients in all columns. The results mean that the volatility in Tokyo's electricity spot market can also be determined by its previous values. The coefficients of $Solar(Tokyo)_d$ are positive and statistically significant in columns (2) and (3), which suggests that local solar power generation leads to an increase in the realized volatility in Tokyo's market. For example, the coefficient is 0.044 for $Solar(Tokyo)_d$ in column (3), which suggests that a 1% increase in local solar power generation leads to a 0.044% increase in realized volatility. This result is consistent with Rintamäki et al. (2017), Ketterer (2014), and Ma et al. (2019), namely, that renewable power generation increases the realized volatility in the local electricity spot market. Meanwhile, $\widehat{Transmission}(Solar)_d$ (columns (2) and (3)) and $\widehat{Transmission}(Wind)_d$ (column (2)) are negatively and significantly correlated with the realized volatility. These results show that increasing the renewable power transmitted from Tohoku reduces the realized volatility in Tokyo's spot market. In particular, a 1% increase in the indirect impacts of Tohoku's solar and wind power generation induces a 0.034% and 0.019% decline in the change in realized volatility, respectively[13]. We consider that lower impacts on wind power is owing to the higher generation of wind power is transmitted from Tohoku that compare with solar power. The coefficient of $Primary(Tohoku)_d$ has a positive and statistically significant sign in column (3), showing that higher base-load and mid-range power leads to increased realized volatility. $TransImpact_d$ is positive and statistically significant in columns (3), which suggests that the electricity transmission excluding renewable power from Tohoku to Tokyo leads to an increase in the realized volatility in Tokyo's spot market. Our findings show opposite impacts of local and transmitted renewable power on the realized volatility in Tokyo. We suggest that the positive impacts of local renewable power generation is due to the relatively unstable supply of the local renewable power, limited access to regulating power, and insufficient transmission capacity of the interconnection line. Rintamäki et al. (2017) concluded that access to flexible capacity through adequate transmission capacity could reduce short-term volatility. We consider that the volatility reduction impact of trans- mitted renewable power is due to the more stable renewable electricity supply from Tohoku (Ma et al., 2019). These results also indicate that the

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[13] The coefficients of the indirect impacts of Tohoku's solar power generation was calculated by product of the coefficients of $Solar(Tohoku)_d$ and $\widehat{Transmission}(Solar)_d$: 0.080 × -0.218 that equal -0.017, and the coefficients of the indirect impacts of Tohoku's wind power generation was calculated by product of the coefficients of $Wind(Tohoku)_d$ and $\widehat{Transmission}(Wind)_d$: 0.032 × -0.333 that equal -0.010.

enhancement of transmission capacity has the potential to increase the stability of the Tokyo market.

Furthermore, we also estimated the impacts on the realized volatility during different intraday periods. The intraday periods were classified into peak time (1:00 p.m.–4:00 p.m.), off-peak time (12:00 a.m.–12:00 p.m. and 5:00 p.m.–12:00 a.m.), daytime (8:00 a.m.–10:00 p.m.) and nighttime (11:00 p.m.–7:00 a.m.). The realized volatility was recalculated based on these sub-samples according to equations (3) and (4)[14]. The results for the first and second stages are shown in Tables 7 and 8, respectively. The results for the estimations during the peak period are listed in column (1) and those for the off-peak period are listed in column (2). Columns (3) and (4) report the results for the estimations during the daytime period and nighttime period, respectively. The coefficients of $Solar(Tohoku)_d$ and $Wind(Tohoku)_d$ in Table 7 suggest that the transmitted power generation from Tohoku can be varied with changes in electricity demand in Tokyo.

[Table 7]

The coefficients of $Solar(Tokyo)_d$ show a positive and statistically significant sign in columns (2) and (3) in Table 8. $Wind(Tokyo)_d$ is positive and statistically significant sign in column (2). The results suggest that local renewable power generation increases realized volatility during the daytime and off-peak periods. In particular, a 1% increase in solar and wind power generation leads to a 0.034% and 0.012% increase, respectively, in the realized volatility in Tokyo's electricity spot market. Meanwhile, $\widehat{Transmission}(Solar)_d$ and $\widehat{Transmission}(Wind)_d$ have negative and statistically significant signs in columns (2) and (3). The result indicates that the volatility reduction impact of transmitted renewable power also can be observed during the daytime and off-peak time. For instance, a 1% increase in solar and wind power transmitted from Tohoku leads to a 0.018% and 0.010% decline in realized volatility during off-peak time, respectively[15]. On the other hand, a 1% increase in solar and wind power transmitted from Tohoku leads to a 0.026% and 0.010% decline in realized volatility during daytime, respectively[16]. Conversely, the insignificant coefficients of the renewable power generation indicators shown in column (4) in Table 8 indicate that both local and transmitted renewable energy do not exert an impact on the realized volatility during the

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[14] For instance, realized volatility during the peak time is calculated as $RV(peaktime)_d = \sum_{t=13}^{15} Return_t^2$.

[15] The coefficients of the indirect impacts of Tohoku's solar power generation during the off-peak time period was calculated by product of the coefficients of $Solar(Tohoku)_d$ in column (2) of Table 7 and $\widehat{Transmission}(Solar)_d$ in column (2) of Table 8: 0.056 × -0.314 that equal -0.018, and the coefficients of the indirect impacts of Tohoku's wind power generation during same period was calculated by product of the coefficients of $Wind(Tohoku)_d$ and $\widehat{Transmission}(Wind)_d$: 0.031 × -0.318 that equal -0.010.

[16] The coefficients of the indirect impacts of Tohoku's solar power generation during the off-peak time period was calculated by product of the coefficients of $Solar(Tohoku)_d$ in column (2) of Table 7 and $\widehat{Transmission}(Solar)_d$ in column (2) of Table 8: 0.138 × -0.188 that equal -0.026, and the coefficients of the indirect impacts of Tohoku's wind power generation during same period was calculated by product of the coefficients of $Wind(Tohoku)_d$ and $\widehat{Transmission}(Wind)_d$: 0.030 × -0.328that equal -0.010.

nighttime.

[Table 8]

These results on realized volatility in different periods indicate that both local renewable and transmitted renewable power generation affect realized volatility during the period with lower electricity demand[17]. The renewable power suppliers have not been incentivized by the FIT scheme to increase production during the period with higher electricity demand (METI, 2020b). This result complements the findings of Schmidt et al. (2013) that FIT does not provide an incentive to match electricity production with the marginal costs of electricity production. The actual marginal cost during peak periods has been higher, and during off-peak periods it has been below average. High marginal cost power plants have been built to operate only during peak periods, with substantial unused capacity during the off-peak (Pikk and Viiding, 2013). Renewable electricity suppliers tend to trade during periods with lower demand to avoid the higher marginal cost and consequently the higher financial risk during peak times.

5. Conclusions

This study examined the impacts of cross-region transmission from Tohoku on the electricity spot market in Tokyo. Our findings indicate that, by providing flexibility in the energy capacity of the local market, the renewable power from neighboring areas plays an important role in the local electricity market. In the study areas, the renewable power power from Tohoku has higher price reduction effects compared to local renewable power generation in Tokyo. The relatively higher effects could be due to higher price elasticity under a tight supply–demand balance. In particular, cross-regional wind power generation has a higher price reduction effect during peak times compared to distributed solar power. The wind power generation can meet the higher electricity demand in the spot market. Therefore, we suggest that increasing investment in the wind industry can help balance the peak time electricity supply–demand. Meanwhile, our results confirm the cross-regional price stabilization impact of renewable power generation in Tohoku. The negative impact on realized volatility is due to the relatively more stable renewable electricity transmitted from Tohoku. However, the current transmission capacity between Tohoku and Tokyo is still limited; this restricts the potential for transmission of renewable power from Tohoku to Tokyo. Therefore, increasing the capacity of the interconnections between Tohoku and Tokyo is a key factor in increasing renewable electricity deployment in Tokyo, leading to further price reductions and stabilization in the spot market.

Furthermore, our results indicate that renewable power producers, especially solar power

[17] According to results in column (2) and (4) in Table 8, a statistically significant impact can be found during the off-peak period except nighttime, which means the period of 8:00 a.m. - 1:00 p.m. and 4:00 p.m. -10:00p.m..

producers, are not incentivized by the fixed-price FIT to meet electricity demand during peak times because of the higher marginal costs. Implementing the feed-in premiums (FIP) scheme can help facilitate demand-based power supply since the premium that producers receive is based on the market price (Marques et al., 2019). Further, the FIP is deemed to provide an incentive to better match renewable power output with marginal production costs. In fact, to achieve the carbon-neutral goal for 2050, the sliding FIP system will be implemented in the Japanese market from April 2022 (METI, 2021). The government expects that renewable power producers will be incentivized to react based on market price signals once the FIT has been replaced with the FIP. However, the government also need to beware the FIP retarding the investment in renewable power technologies[18]. Moreover, we suggest that increasing the usage of aggregator services can increase the stability of renewable power output and thus induce further price reduction effects during peak periods.

[18] Du and Ma (2021) discuss the implement of FIP in Germany and indiating that FIP achieved its objective of encouraging the market integration of wind energy but retard the investment in solar power technologies in Germany.

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Table 1: Annual utilization of cross-regional interconnection lines for regional service areas in fiscal years (50Hz areas)

[GWh]

		2010	2011	2012	2013	2014	2015	2016	2017	2018	2019
Hokkaido–Honshu	→ Tohoku (Forward)	972	3,925	214	182	143	146	237	340	130	279
	→ Hokkaido (Counter)	12	7	673	505	617	804	1,033	1,270	1,005	2,117
Tohoku–Tokyo	→ Tokyo (Forward)	27,519	9,454	16,084	22,450	21,273	22,587	23,097	28,238	27,298	27,575
	→ Tohoku (Counter)	12,219	5,674	4,520	3,891	4,029	3,714	4,660	7,071	3,139	252
Tokyo–Chubu	→ Chubu (Forward)	188	1,151	1,579	2,829	2,702	693	2,729	3,954	1,711	354
	→ Tokyo (Counter)	1,271	2,426	1,288	536	2,755	4,513	5,144	5,328	5,116	4,147

Source: Outlook of Electricity Supply–Demand and Cross-regional Interconnection Lines: Actual Data for FY 2019 (OCCTO, 2020)

Table 2: Descriptive statistics

Variable	Unit	N	Mean	Std. Dev.	Min	Max
Panel A: Hourly data summarization						
$Price_t$	Yen/kWh	35,064	9.818	4.322	1	60.01
$Solar(Tokyo)_t$	MWh	35,064	1,603	2,484	0	11,300
$Wind(Tokyo)_t$	MWh	35,064	106.9	77.33	0	450
$Forecast(Tokyo)_t$	MWh	34,824	27,142	13,914	0	56,940
$Primary(Tokyo)_t$	%	35,064	0.863	0.079	0.519	1.209
$Solar(Tohoku)_t$	MWh	35,064	575.8	909.4	0	4,816
$Wind(Tohoku)_t$	MWh	35,064	277.8	233.9	0	1,123
$Forecast(Tohoku)_t$	MWh	32,904	8,335	3,516	0	14,580
$Primary(Tohoku)_t$	%	35,064	1.158	0.113	0.674	1.536
FIT_t	Yen/kWh	35,064	19.25	3.701	14	24
$Transmission_t$	MWh	35,064	2,544	726.2	-59	4,993
Panel B: Daily data summarization						
RV_d	%	1,461	0.435	0.548	0.008	4.702
$Solar(Tokyo)_d$	MWh	1,461	38,461	18,352	740	84,140
$Wind(Tokyo)_d$	MWh	1,461	2,566	1,631	150	8,960
$Forecast(Tokyo)_d$	MWh	1,461	646,939	320,102	0	1,088,170
$Primary(Tokyo)_d$	%	1,461	0.857	0.410	0.729	0.955
$Solar(Tohoku)_d$	MWh	1,461	13,819	7,860	735	37,357
$Wind(Tohoku)_d$	MWh	1,461	6,668	4,979	265	23,797
$Forecast(Tohoku)_d$	MWh	1,461	187,708	92,964	0	321,670
$Primary(Tohoku)_d$	%	1,461	1.153	0.0649	0.916	1.381
$Transmission_d$	MWh	1,461	61,053	15,920	24,725	107,770

Note: **Panel A** shows the descriptive statistics for hourly dataset, and **Panel B** shows the descriptive statistics for daily dataset.

Table 3: The impact of renewable power generation on cross-regional interconnection line (hourly)

$Transmission_t$	(1)	(2)	(3)
$lag(1\ hour)Transmission_t$	0.797***	0.772***	0.763***
	(0.041)	(0.047)	(0.052)
$lag(1\ day)Transmission_t$	0.151***	0.138***	0.112***
	(0.028)	(0.027)	(0.024)
$lag(1\ week)Transmission_t$	0.045***	0.043***	0.026***
	(0.010)	(0.010)	(0.006)
$Solar(Tohoku)_t$	0.000	0.004***	0.011***
	(0.000)	(0.001)	(0.001)
$Wind(Tohoku)_t$	0.000	0.006***	0.006***
	(0.000)	(0.001)	(0.001)
$Primary(Tohoku)_t$		0.227***	0.358***
		(0.037)	(0.048)
$D\_Forecast(Tohoku)_t$		-0.650***	-0.556***
		(0.064)	(0.025)
$D\_Forecast(Tokyo)_t$		0.489***	0.484***
		(0.033)	(0.021)
Constant	0.060	0.064	0.309**
	(0.057)	(0.060)	(0.153)
Time dummy variables	No	No	Yes
N	34,891	32,808	32,808
R^2	0.918	0.923	0.930

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The robust option was used for all of the models. Year, month, and hour dummy variables were used in column (3). The $D\_Forecast(Tohoku)_t$ and $D\_Forecast(Tokyo)_t$ were used to represent the first order difference terms of $Forecast(Tohoku)_t$ and $Forecast(Tokyo)_t$ because null hypothesis was not rejected by Augmented Dickey-Fuller (ADF) unit root test, indicating that the series was not stationary for these variables. By using the log-log specification equation, all coefficients show the supply elasticity of the variables except $Primary_t$, and dummy variables.

Table 4: The impact of renewable power generation on electricity spot price

$Price_t$	(1)	(2)	(3)	(4)	(5)
$lag(1\ hour)Price_t$	0.792***	0.793***	0.792***	0.793***	0.791***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
$lag(1\ day)Price_t$	0.113***	0.111***	0.110***	0.109***	0.110***
	(0.005)	(0.005)	(0.005)	(0.005)	(0.005)
$lag(1\ week)Price_t$	0.076***	0.075***	0.075***	0.074***	0.074***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
$Solar(Tokyo)_t$	-0.019***	-0.008***	-0.006***	-0.006***	-0.006***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
$Wind(Tokyo)_t$	-0.003***	-0.002***	-0.002***	-0.002**	-0.002***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
$\widehat{Transmission}(Solar)_t$		-1.258***	-1.226***	-1.316***	-0.933***
		(0.107)	(0.118)	(0.119)	(0.122)
$\widehat{Transmission}(Wind)_t$		-0.552***	-0.472***	-0.339***	0.674***
		(0.125)	(0.125)	(0.128)	(0.137)
FIT_t			-0.002***	-0.002***	-0.002***
			(0.000)	(0.000)	(0.000)
$Primary(Tokyo)_t$			0.121***	0.137***	0.111***
			(0.015)	(0.015)	(0.015)
$TransImpact_t$			0.003	0.003	0.002
			(0.003)	(0.003)	(0.003)
$D\_Forecast(Tokyo)_t$			0.126	0.125	0.125
			(0.094)	(0.093)	(0.093)
$Peak_t$				0.068**	
				(0.030)	
$Peak_t \times \widehat{Transmission}(Solar)_t$				1.242***	
				(0.309)	
$Peak_t \times \widehat{Transmission}(Wind)_t$				-1.092***	
				(0.346)	
$Daytime_t$					0.056***
					(0.009)
$Daytime_t \times \widehat{Transmission}(Solar)_t$					-0.587***
					(0.100)
$Daytime_t \times \widehat{Transmission}(Wind)_t$					-1.847***
					(0.179)
Constant	-0.011	0.003	-0.083**	-0.100***	-0.100***
	(0.011)	(0.011)	(0.036)	(0.036)	(0.036)
Time dummy variables	No	Yes	Yes	Yes	Yes
N	34,896	34,891	34,818	34,818	34,818
R^2	0.879	0.880	0.881	0.881	0.881

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The robust option was used for all of the models. Year, month, and hour dummy variables were used in columns (2) – (5). The $D\_Forecast(Tokyo)_t$ was used to represent the first order difference term of $Forecast(Tokyo)_t$ because null hypothesis was not rejected by Augmented Dickey-Fuller (ADF) unit root test, indicating that the series was not stationary for this variable. By using the log-log specification equation, all coefficients show the price elasticity of the variables $\widehat{Transmission}(Solar)_t$, $\widehat{Transmission}(Wind)_t$, $TransImpact_t$, $Primary_t$, FIT_t, and dummy variables.

Table 5: The impact of renewable power generation on cross-regional interconncetion line (daily)

$Transmission_d$	(1)	(2)	(3)
$lag(1\ day)Transmission_d$	0.820***	0.570***	0.458***
	(0.021)	(0.020)	(0.022)
$lag(1\ week)Transmission_d$	0.129***	0.099***	0.040**
	(0.020)	(0.015)	(0.016)
$Solar(Tohoku)_d$	0.001	0.067***	0.080***
	(0.005)	(0.006)	(0.006)
$Wind(Tohoku)_d$	0.002	0.041***	0.032***
	(0.003)	(0.003)	(0.003)
$Primary(Tohoku)_d$		1.500***	1.851***
		(0.066)	(0.072)
$D\_Forecast(Tohoku)_d$		-0.311***	-0.212***
		(0.071)	(0.064)
$D\_Forecast(Tokyo)_d$		0.278***	0.187***
		(0.065)	(0.058)
Constant	0.535***	0.930***	2.387***
	(0.130)	(0.108)	(0.204)
Time dummy variables	No	No	Yes
N	1,454	1,454	1,454
R^2	0.857	0.909	0.924

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The robust option was used for all of the models. Year and month dummy variables were used in column (3). The $D\_Forecast(Tohoku)_d$ and $D\_Forecast(Tokyo)_d$ were used to represent the first order difference terms of $Forecast(Tohoku)_d$ and $Forecast(Tokyo)_d$ because null hypothesis was not rejected by Augmented Dickey-Fuller (ADF) unit root test, indicating that the series was not stationary for these variables. By using the log-log specification equation, all coefficients show the supply elasticity of the variables except $Primary_d$, and dummy variables.

Table 6: The impact of renewable power generation on realized volatility

RV_d	(1)	(2)	(3)
$lag(1\ day)RV_d$	0.427***	0.425***	0.401***
	(0.040)	(0.040)	(0.040)
$lag(1\ week)RV_d$	0.231***	0.231***	0.224***
	(0.034)	(0.034)	(0.034)
$Solar(Tokyo)_d$	0.012	0.034**	0.064***
	(0.010)	(0.013)	(0.018)
$Wind(Tokyo)_d$	0.008	0.013	0.016
	(0.008)	(0.012)	(0.012)
$\widehat{Transmission}(Solar)_d$		-0.431**	-0.318*
		(0.194)	(0.188)
$\widehat{Transmission}(Wind)_d$		-0.588*	-0.484
		(0.324)	(0.317)
$Primary(Tokyo)_d$			1.375***
			(0.347)
FIT_d			0.001
			(0.003)
$TransImpact_d$			0.125**
			(0.053)
$D\_Forecast(Tokyo)_d$			0.021
			(0.022)
Constant	-0.020	0.182	-2.868***
	(0.128)	(0.154)	(0.844)
Time dummy variables	No	No	Yes
N	1,454	1,454	1,454
R^2	0.370	0.374	0.385

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The robust option was used for all of the models. Year and month dummy variables were used in columns (2) − (3). The $D\_Forecast(Tokyo)_d$ was used to represent the first order difference term of $Forecast(Tokyo)_d$ because null hypothesis was not rejected by Augmented Dickey-Fuller (ADF) unit root test, indicating that the series was not stationary for this variable. By using the log-log specification equation, all coefficients show the price elasticity of the variables except $\widehat{Transmission}(Solar)_d$, $\widehat{Transmission}(Wind)_d$, $TransImpact_d$, $Primary_d$, FIT_d, and dummy variables.

Table 7: The impact of renewable power generation on cross-regional interconnection line (divided by periods)

RV_d	(1)	(2)	(3)
$lag(1\ day)RV_d$	0.427***	0.425***	0.401***
	(0.040)	(0.040)	(0.040)
$lag(1\ week)RV_d$	0.231***	0.231***	0.224***
	(0.034)	(0.034)	(0.034)
$Solar(Tokyo)_d$	0.012	0.034**	0.064***
	(0.010)	(0.013)	(0.018)
$Wind(Tokyo)_d$	0.008	0.013	0.016
	(0.008)	(0.012)	(0.012)
$\widehat{Transmission}(Solar)_d$		-0.431**	-0.318*
		(0.194)	(0.188)
$\widehat{Transmission}(Wind)_d$		-0.588*	-0.484
		(0.324)	(0.317)
$Primary(Tokyo)_d$			1.375***
			(0.347)
FIT_d			0.001
			(0.003)
$TransImpact_d$			0.125**
			(0.053)
$D\_Forecast(Tokyo)_d$			0.021
			(0.022)
Constant	-0.020	0.182	-2.868***
	(0.128)	(0.154)	(0.844)
Time dummy variables	No	No	Yes
N	1,454	1,454	1,454
R^2	0.370	0.374	0.385

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The robust option was used for all of the models. Year and month dummy variables were used in columns (2) − (3). The $D\_Forecast(Tokyo)_d$ was used to represent the first order difference term of $Forecast(Tokyo)_d$ because null hypothesis was not rejected by Augmented Dickey-Fuller (ADF) unit root test, indicating that the series was not stationary for this variable. By using the log-log specification equation, all coefficients show the price elasticity of the variables except $\widehat{Transmission}(Solar)_d$, $\widehat{Transmission}(Wind)_d$, $TransImpact_d$, $Primary_d$, FIT_d, and dummy variables.

Table 8: The impact of renewable power generation on realized volatility (divided by periods)

$Transmission_d$	(1) Peak	(2) Off-peak	(3) Daytime	(4) Nighttime
$lag(1\ day)Transmission_d$	0.325***	0.476***	0.391***	0.468***
	(0.021)	(0.022)	(0.021)	(0.035)
$lag(1\ week)Transmission_d$	0.080***	0.034**	0.061***	0.015
	(0.019)	(0.015)	(0.017)	(0.015)
$Solar(Tohoku)_d$	0.235***	0.056***	0.138***	-0.004*
	(0.013)	(0.005)	(0.009)	(0.002)
$Wind(Tohoku)_d$	0.033***	0.031***	0.030***	0.040***
	(0.003)	(0.003)	(0.003)	(0.003)
$Primary(Tohoku)_d$	1.947***	1.837***	1.949***	1.969***
	(0.073)	(0.073)	(0.075)	(0.117)
$D\_Forecast(Tohoku)_d$	-0.256***	-0.203***	-0.204***	-0.263***
	(0.058)	(0.065)	(0.061)	(0.072)
$D\_Forecast(Tokyo)_d$	0.212***	0.180***	0.174***	0.239***
	(0.052)	(0.060)	(0.056)	(0.066)
Constant	1.085***	2.452***	2.054***	2.568***
	(0.197)	(0.199)	(0.201)	(0.254)
Time dummy variables	Yes	Yes	Yes	Yes
N	1,454	1,454	1,454	1,454
R^2	0.855	0.929	0.897	0.933

Note: Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$. The robust option was used for all of the models. Year and month dummy variables were used in all columns. The $D\_Forecast(Tohoku)_d$ and $D\_Forecast(Tokyo)_d$ were used to represent the first order difference terms of $Forecast(Tohoku)_d$ and $Forecast(Tokyo)_d$ because null hypothesis was not rejected by Augmented Dickey-Fuller (ADF) unit root test, indicating that the series was not stationary for these variables. By using the log-log specification equation, all coefficients show the supply elasticity of the variables except $Primary_d$, and dummy variables.

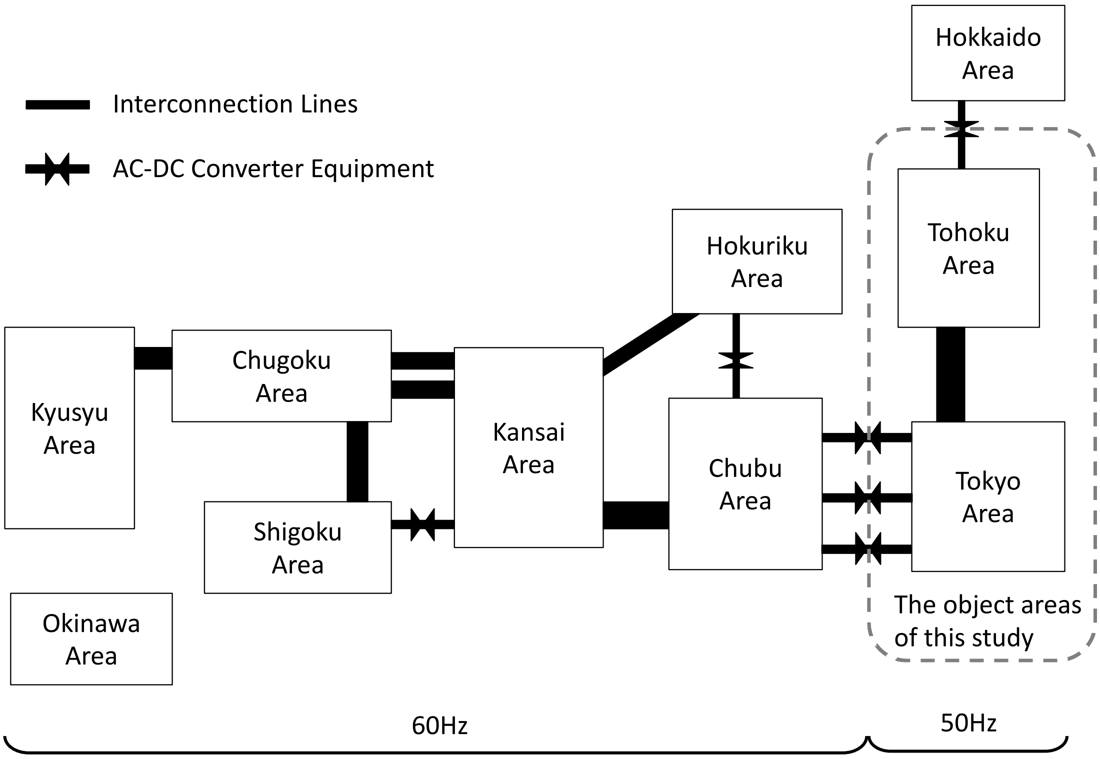

Figure 1: The object areas in this study

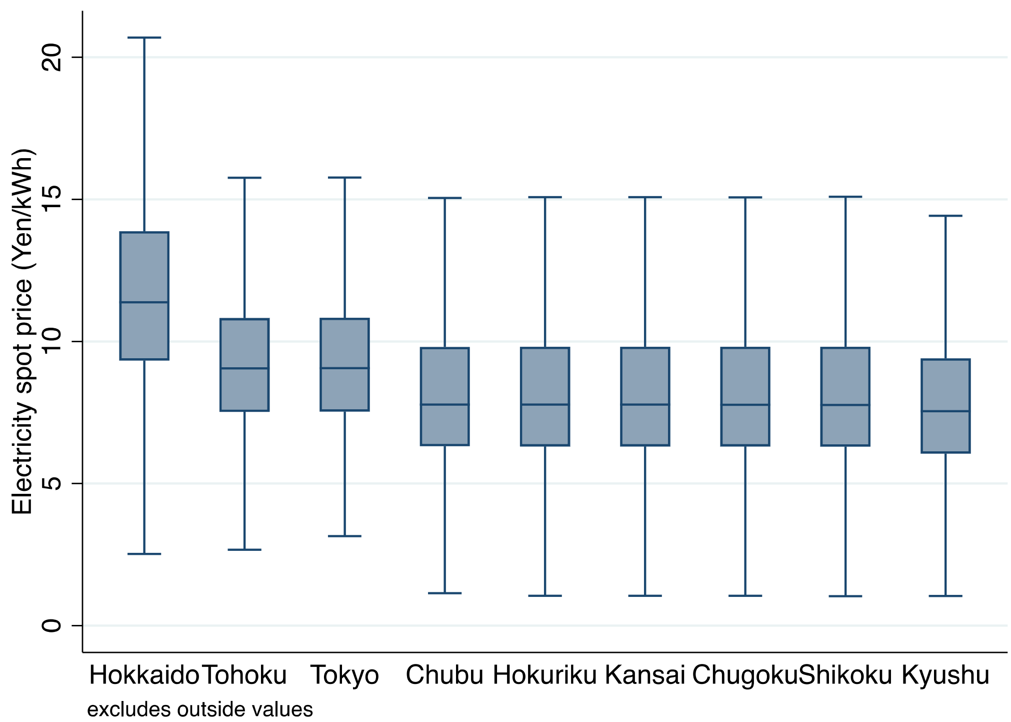

Figure 2: Electricity spot price in nine regions (FY2016–FY2019)

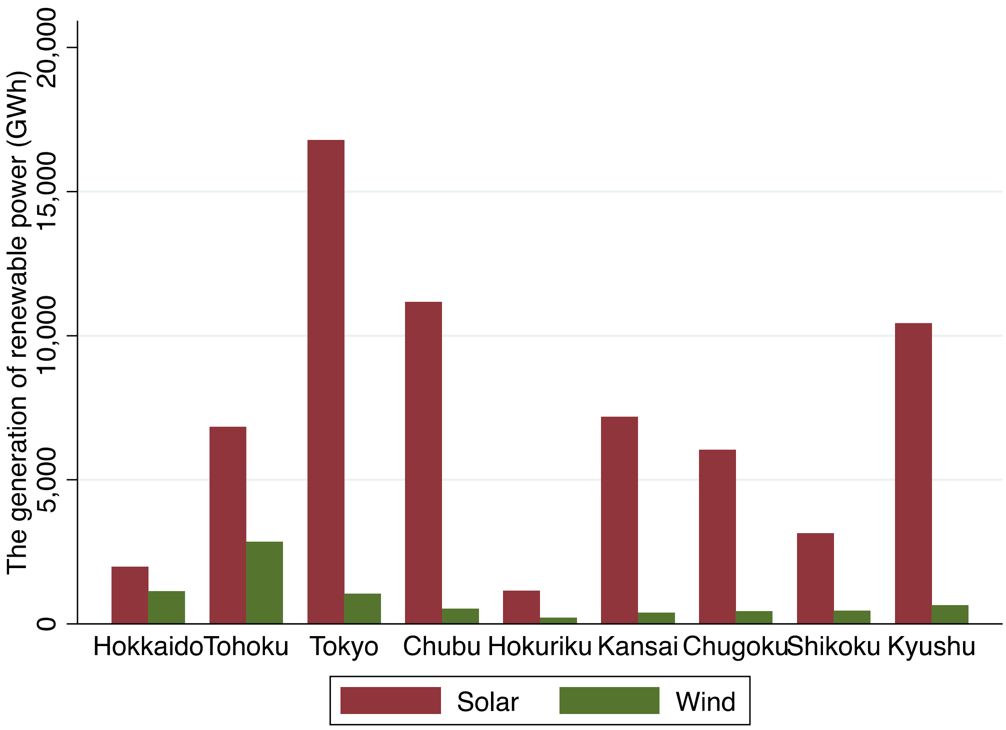

Figure 3: Renewable power generation in FY 2019

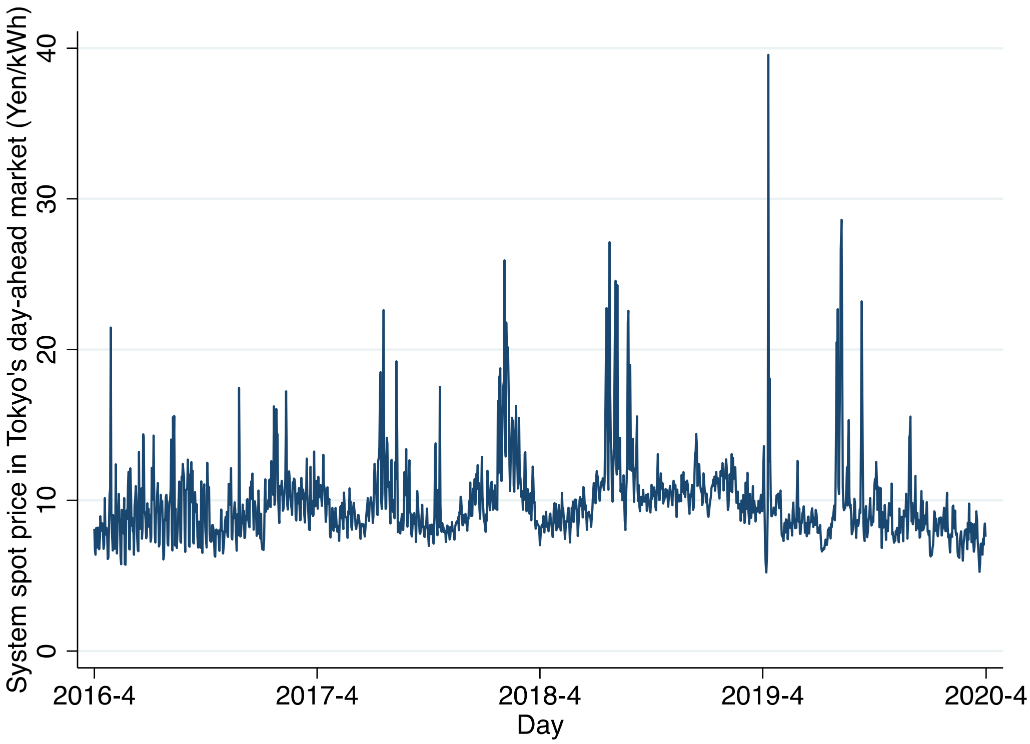

Figure 4: Trends in daily system spot price in Tokyo's electricity spot market (FY2016–FY2019)

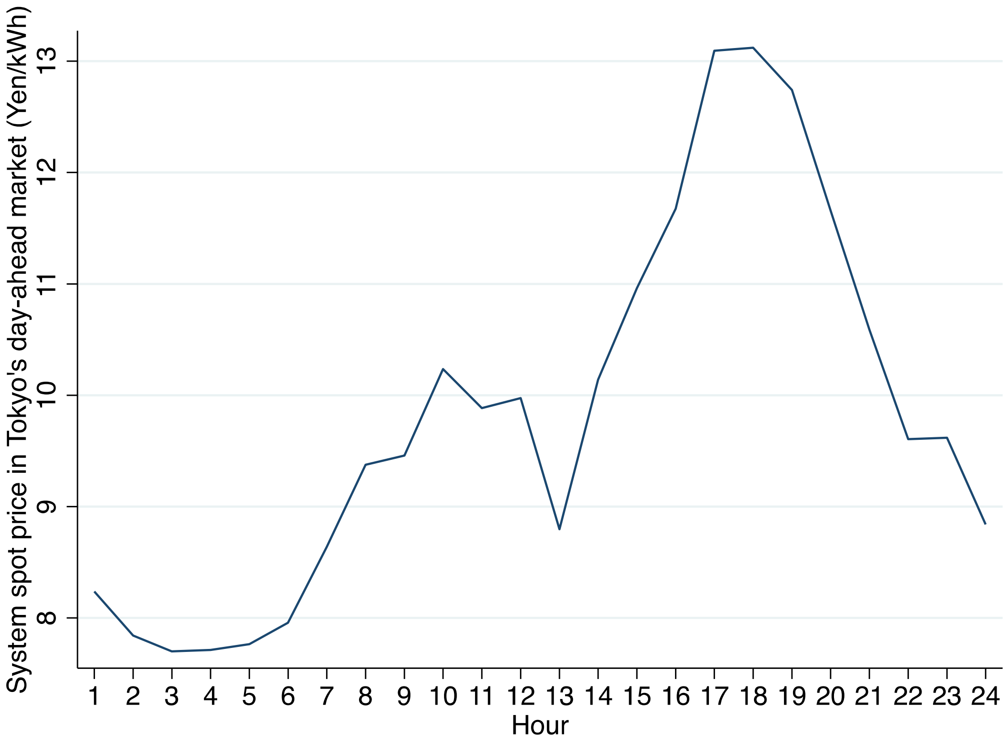

Figure 5: Trends in hourly system spot price in Tokyo's electricity spot market (FY2016–FY2019)

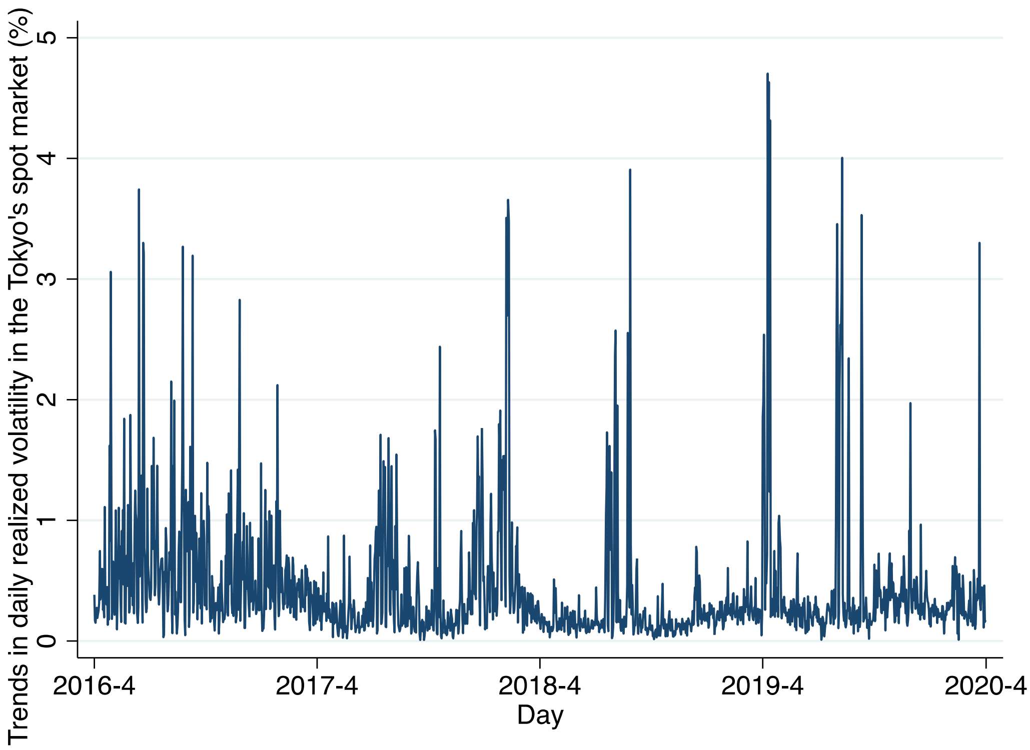

Figure 6: Trends in daily realized volatility in the Tokyo's spot market (FY2016–FY2019)

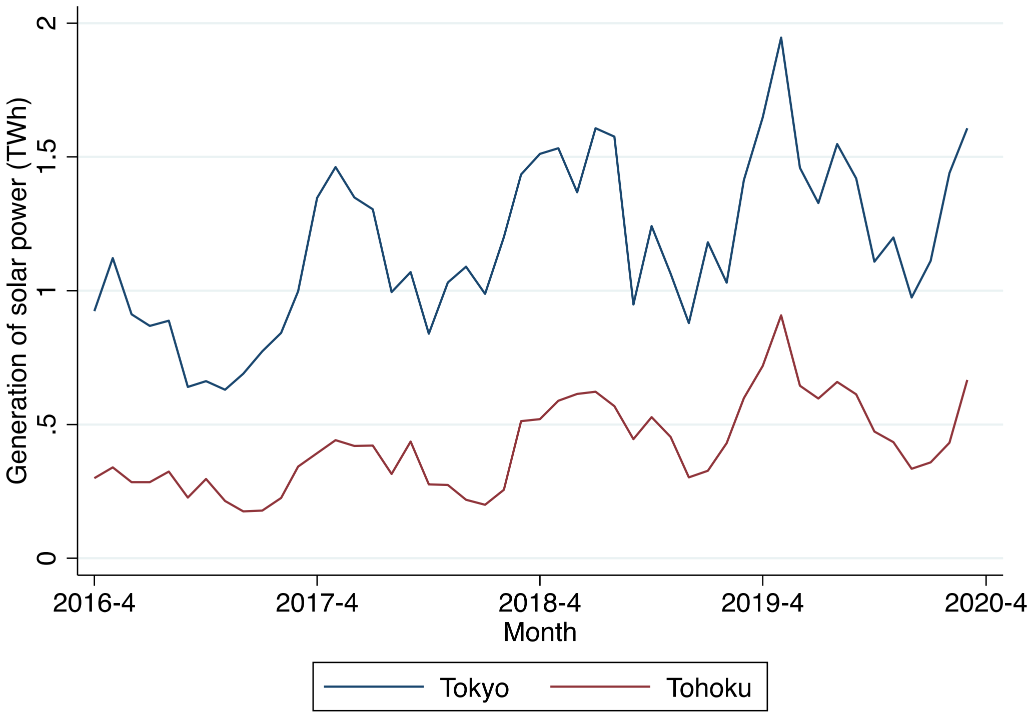

Figure 7: Trends in monthly solar power generation (FY2016–FY2019)

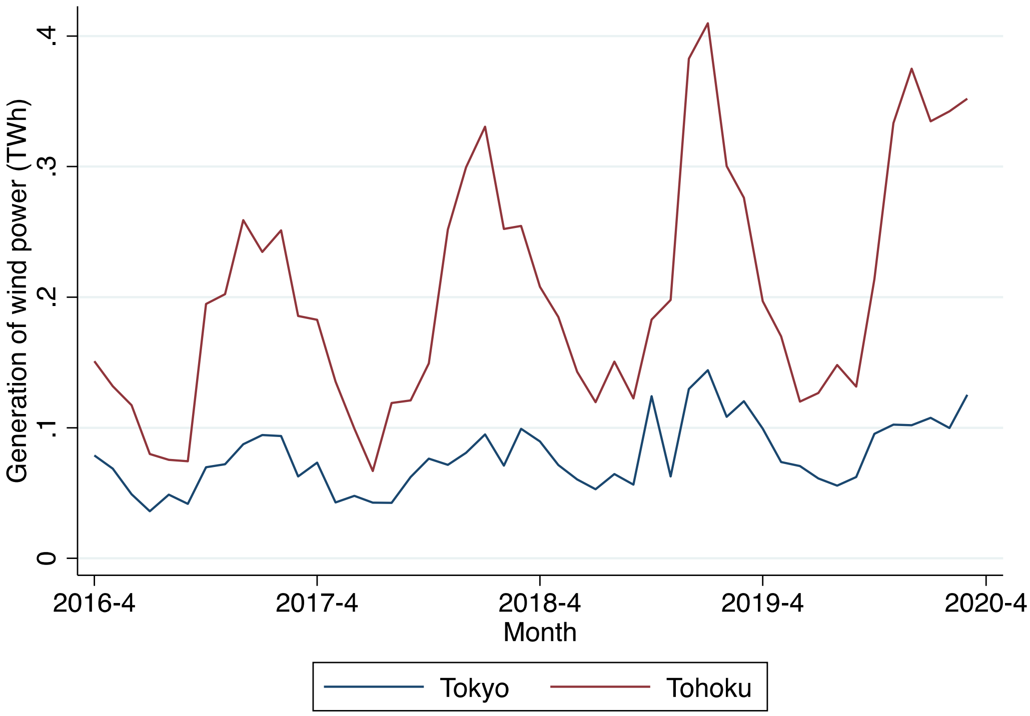

Figure 8: Trends in monthly wind power generation (FY2016–FY2019

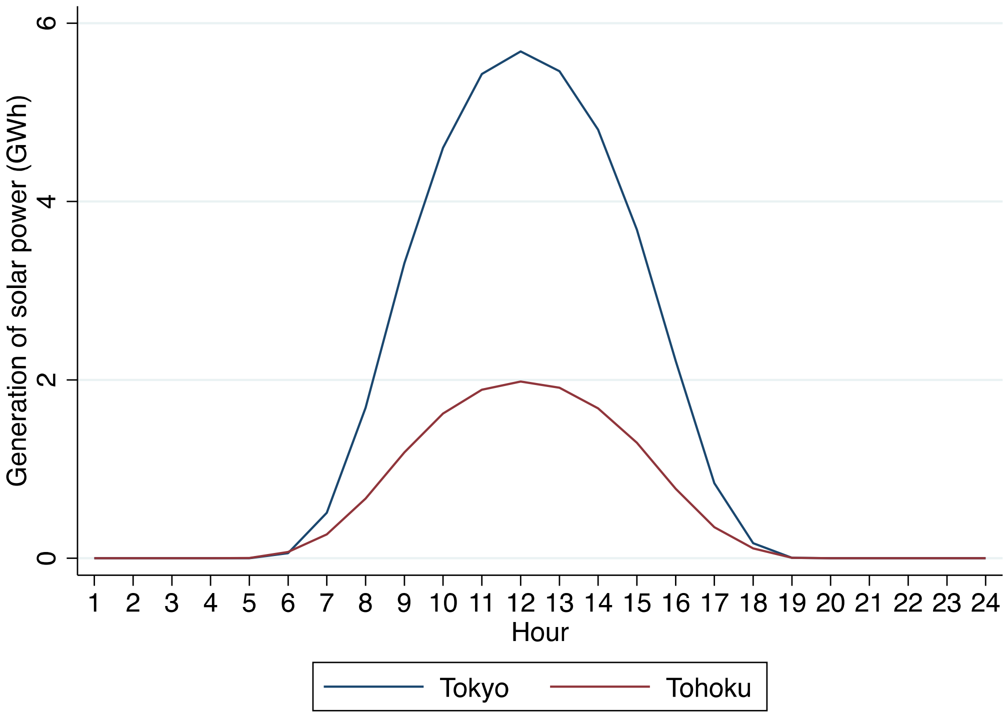

Figure 9: Trends in hourly solar power generation (FY2016–FY2019)

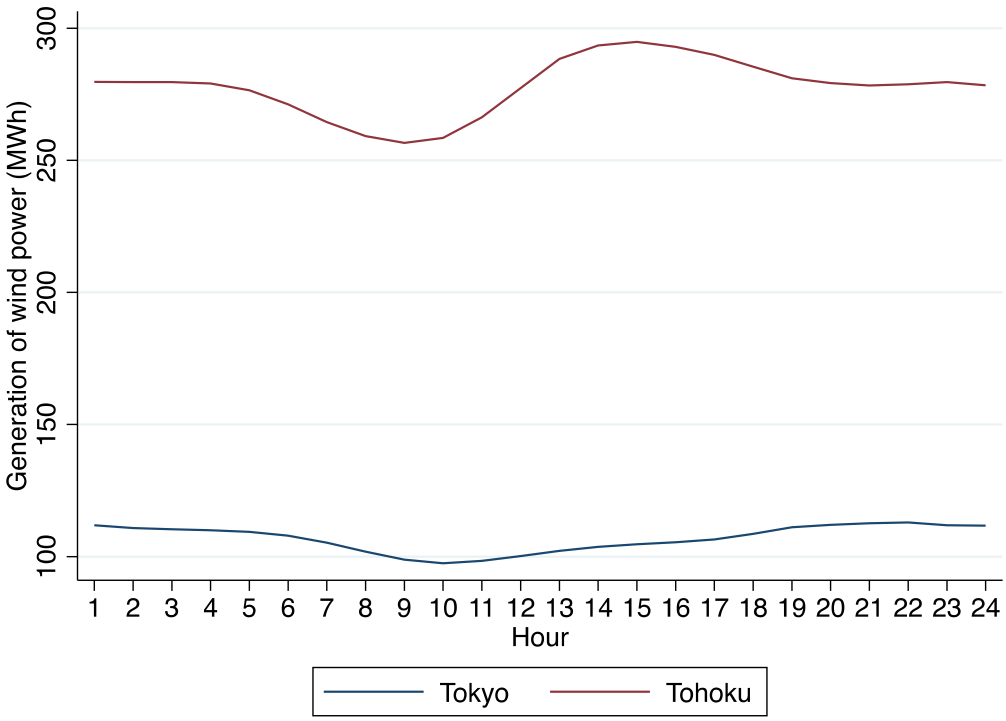

Figure 10: Trends in hourly wind power generation (FY2016–FY2019)

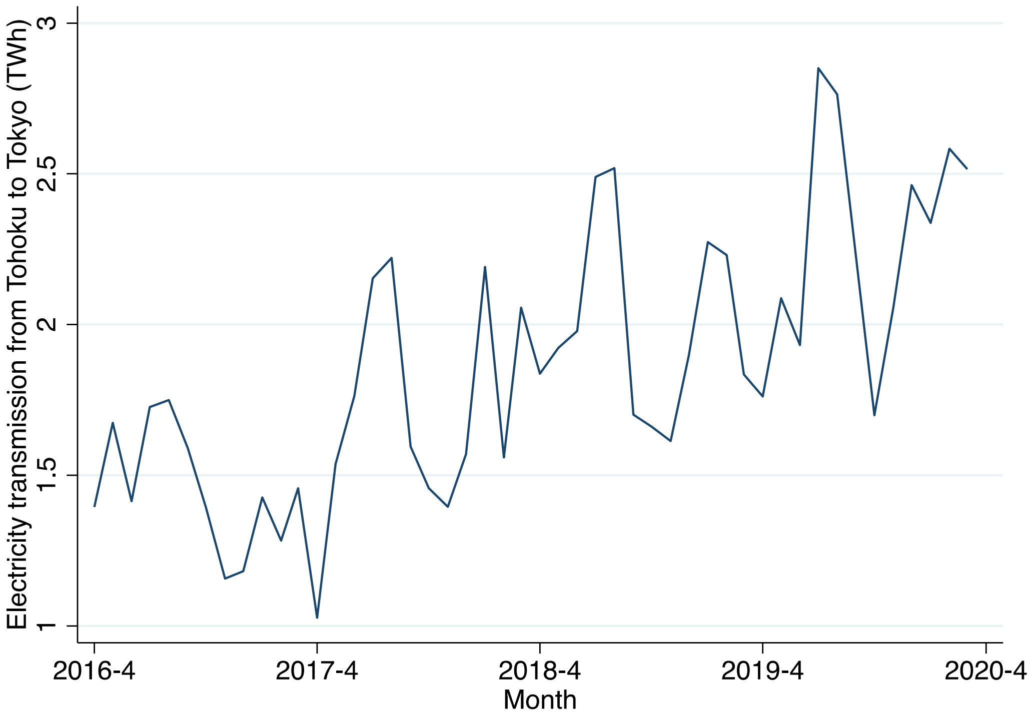

Figure 11: Trends in monthly electricity transmission from Tohoku to Tokyo (FY2016–FY2019)

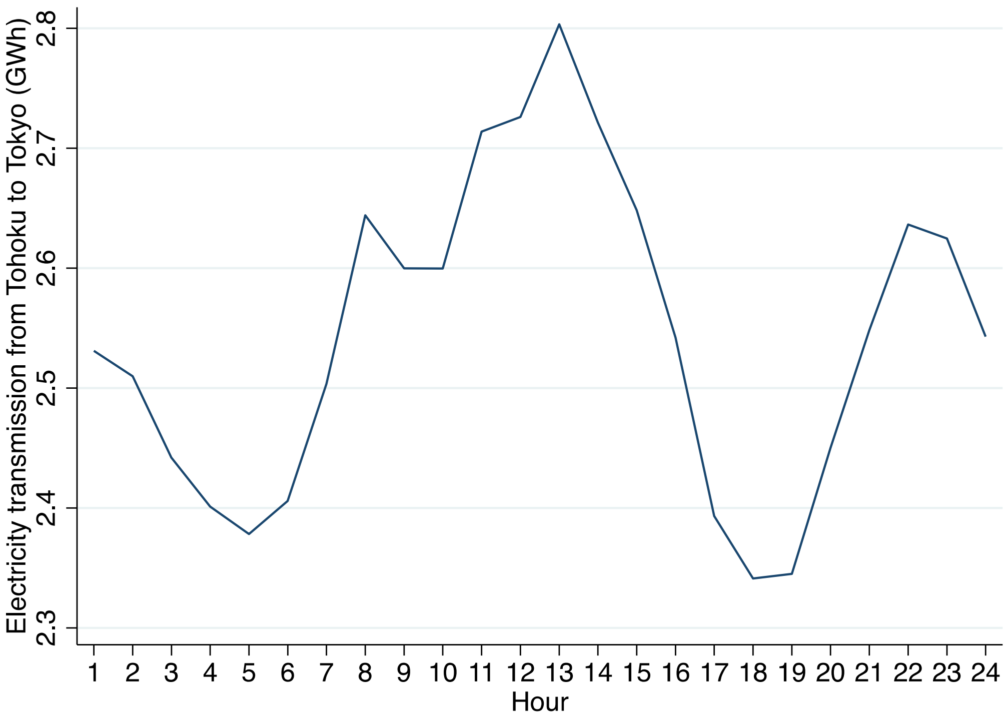

Figure 12: Trends in hourly electricity transmission from Tohoku to Tokyo (FY2016–FY2019)