Discussion Paper
Research Project on Renewable Energy Economics,
Graduate School of Economics, Kyoto University

Renewable Energy Generation Effects on the Electricity Market: An Empirical Study on Japan's Electricity Spot Market

31th May 2020

Teng MA[a], Yimeng DU[b], Tao XU[c]

[a] Graduate School of Economics, Kyoto University
[b] Graduate School of Economics, Kyoto University
[c] Business School, Hunan Normal University

Impact of dynamic pricing strategy of electricity on residential energy consumption decisions in China: Empirical evidence from a household survey

Teng MA[a], Yimeng DU[b], Tao XU[c]

[a] Graduate School of Economics, Kyoto University
[b] Graduate School of Economics, Kyoto University
[c] Business School, Hunan Normal University

Abstract:

This study examines the impact of renewable electricity supply on Japan's electricity spot market. By using the renewable electricity generation data collected from nine traditional electric power companies, as well as the spot price data collected from Japan Electric Power Exchange, we examine both the impact of renewable electricity supply on Japan's electricity spot market and how this impact was influenced by regional differences. Our results indicate that the increase in solar power generation has caused a reduction in spot electricity prices in Japan, while such an impact cannot be observed in the wind power sector. Furthermore, our results illustrate that regional differences also exist in Japan's spot market. We assume that the available transfer capabilities of cross-regional interconnection lines, the scale of regional spot market, and the transaction volume are important factors that affect the impact of renewable electricity generation on spot prices.

Keywords: Spot Market, Renewable Electricity, Regional effects, Japan

1. Introduction

Japan's *1st* System Reform, implemented in 1995, introduced competition to the country's wholesale electricity market[1] (METI, 2018). After the *2nd* System Reform in 1999, the market liberalization was extended retail choice to cover special, high-voltage customers[2]. As newcomers to Japan's electricity market, Power Producers and Suppliers (PPS) were allowed to supply electricity to eligible consumers in the wholesale electricity market[3] (Tokyo Electric Power Company Holdings[a]). Moreover, in order to both encourage more active electric power exchange and encourage diversity in electric power procurement, the Japan Electric Power Exchange (JEPX) was established after the 3rd System Reform in April 2005 (Nakajima, 2013).

The JEPX was founded in an attempt to promote the domestic trade of renewable electricity. As well as the deepening of the electricity reforms, the trading of wholesale electricity via JEPX has been attracting growing levels of attention. The share of trading volume (contract volume) at JEPX in the total electricity demand was less than 2% for a long time. However, the value has been increased in accordance with the launch of the 5th System Reform in April 2016[4] The share of trading volume at JPEX as a share of the total electricity demand increased to 29.0% by 2018, which already exceeded the share in France (25.0%) at the same time (METI, 2018).

On the other hand, the issue of electricity shortages caused by the shutdown of nuclear power plants after the Great East Japan Earthquake has been identified and addressed[5]. In order to increase and stabilize the electricity supply, Japan's government issued the *4th* Strategic Energy Plan on April 2014. The plan reflected two basic principles, the so called "3E+S", which emphasizes "the need to look at both supply and demand side options". 3E+S means energy security, economic efficiency, environmental protection, and safety. (METI, 2014). The plan aimed to expand the size of the renewable sector in Japan's electricity market.

Japan's government has made significant progress in increasing the share of renewable energy since 2012. This has been achieved by continuous active promotion, such as the introduction of the Feed-In Tariff (FIT) scheme and deregulation measures (METI, 2014). On the other hand, the government has also announced plans to increase the share of renewable

---

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

2 20,000 V or higher, with contracted power of at least 2,000 kW as a rule.

3 Japan's electricity market had been completely monopolized by the ten local electricity companies until the system reforms.

4 Since the second phase of the fifth electricity market reform began in 2016, Japan's electricity market has been opened up to competition. The ultimate objective of this reform is to separate the transmission, distribution, and generation of electricity in Japan by 2020. The electricity market reforms are intended to meet the following three government objectives: to secure a stable supply of electricity, to lower electricity prices, and to provide greater choice for consumers through competition amongst business entities (Wakiyama and Kuriyama, 2018).

5 During the post-Fukushima era, the Japanese government shut down and implemented rigorous safety reviews for each of the 60 nuclear power plant units. Only 9 reactors passed the review and were allowed to restart (Oka, 2019).

energy in the country's total power generation from 14.5% in 2016 to 22-24% by 2030 (Ministry of Economy, Trade and Industry (METI, 2015). Furthermore, due to the fact that renewable electricity was virtually not traded on the Japanese electricity spot market until recently, the share of renewable electricity accounted for only approximately 1% of the JEPX spot market in 2015 (METI, 2016). However, along with the deepening of the reforms, renewable electricity suppliers are expected to play an important role in this market. In particular, after the full liberalization of the retail electricity market, various electricity utilities have entered into the market, which has stimulated competition. This has made it possible to trade renewable electricity directly from the suppliers in the market.

We found that most of the current studies focus on Japan's electricity spot market only discussed the process of spot price formation. Using publicly available data from JEPX, Ofuji and Yamaguchi (2008) aimed to identify the magnitude of the impact of selling and buying bids based on the auctioned prices and quantity, and thereby to forecast prices and quantity for risk management purposes. Their results show that the buying bid volumes have the greatest impact among the factors considered, exhibiting time-dependent changes that ranged as much as 240% from the average. Nakajima (2013) investigated whether the power price could be determined using information from primary energy and exchange markets that directly affect the cost of power generation. The results indicate no Granger causality regarding the prices of oil and gas and the exchange rate regarding the price of electricity. Inoue and Tanaka (2018) analyzed electricity price forecasting methods for monthly electricity system prices in the JEPX spot market. They conclude that ARIMAX and NN models can successfully predict the prices, with the prediction error being around kWh per Yen (below 9%). However, these studies do not fully address the system of price formation, or how it is affected by renewable electricity generation.

On the other hand, existing studies in both the U.S. and European countries have mainly focused on renewable electricity trading in the spot market. Existing literatures on the impact of renewable energy generation on the spot market suggest that the electricity spot market can be benefit from an increase in wind power generation. In terms of a competitive market, increasing the penetration of wind power is argued to reduce wholesale spot prices, as the increase in wind generation displaces marginal generation with a high fuel cost (EWEA, 2010). Sensfuβ et al. (2008) analyzed the effect of renewable electricity generation on spot market prices in Germany based on the PowerACE Cluster System. Their results indicate that an increase in renewable electricity generation leads to a considerable price reduction. For instance, the increased use of renewable energy led to a considerable reduction of the average market price by 7.83 EUR in 2006, which in turn simulated renewable generation by up to 52,200 GWh. On the other hand, by using Texas-based 15-min data on balancing the energy market price within each of the four electricity markets in Texas, Woo et al., (2011) estimated the parameters of a partial-adjustment linear regression model of spot electricity prices. The results show that rising wind generation tends to reduce the level of spot prices. In addition, they also argue that wind generation is likely to enlarge the spot-price variance. The conclusions of these studies indicate that increasing the amount of electricity generated by renewable power benefits the electricity spot market, while none of them have thus far conducted a thorough analysis of the regional differences.

In order to fill the research gap that has mentioned above, this study investigates how the increase in renewable-source electricity generation affect spot-market electricity prices, as well as whether their relationship is similar to that observed in the American and European electricity markets. In particular, we focus on the impacts of electricity generated by solar and wind power. Additionally, we also analyze whether regional differences caused by differences in nature resources among regions exist in the spot electricity market.

The remainder of this paper is organized as follows. Section 2 presents the background to this study. We introduce the outline of transaction in JEPX, and explain the combination of Power Sources and Renewable electricity in Japan. Section 3 describes the empirical methodology and data used in the analyzes. The estimation results and discussions are provided in Section 4. Finally, Section 5 presents our conclusions, as well as implications of the research.

2. Background

2.1. JEPX Market

In order to ensure a fair competition in Japan's wholesale electricity market, the JEPX was established on April 2, 2005 (Nakajima, 2013). As of June 2018, a total of 141 trading members trade electricity in the JEPX[6].

JEPX provides several types of wholesale electric power market in Japan. Both the spot market (Day-ahead Market) and forward market were established when the JEPX was first built in 2005. The spot market is the market in which electricity to be delivered next day is traded. Under the single price auction system, a bid is made for the combination of the price and quantity of each product. The forward market is the market for bulletin board products, in which participants freely post matters related to electricity trading. The transaction can be traded from one year or more before to 1 week before. The intraday market was established in April 2016 to supplement the day-ahead market, and help secure the necessary balance between supply and demand in electricity market. The market takes place every day round the clock until 1 hour before delivery. In addition, in order to increase the ratio of non-fossil electricity sources, a non-fossil value trading market was also established in April 2017[7].

[6] The members include not only the General Electricity Utilities, such as Tokyo Electric Power and Kansai Electric Power, but also PPS companies.

[7] The market only trades renewable electricity sources which have been registered in the FIT system since April 2017. Other

Furthermore, in 2019 a base-load power market was proposed in order to promote competition. The market ensures equal access to cheap power supplies for new power retail companies as part of reforms designed to foster competition in the market.

The focus of this study is the spot market, which is the main market of JEPX. Approximately 93% of electricity trading occurred in the spot market during the fiscal year of 2017[8]. As shown in Figure 1, the transactions of the spot market have increased progressively since the JEPX market was first built. We found that the electricity trading was downplayed in the first few years, whereby, for a long period, the share of trading volume relative to the total electricity demand in JEPX was less than 2%. However, this figure has started to increase along with the progress of the marketization reform of April 2016[9]. The trading value was increased to 350 GWh on April 2, 2018, which was about 713 times the trading value on the opening day. The trading volume of the spot market made up 18.4% of the total electricity demand in June 2018. This value is 3.7 times what it was in the same period the previous year (METI, 2017). However, the trading volume was still relatively low compared to electricity markets in Europe[10].

[Figure 1]

2.2. Combination of Power Sources and Renewable electricity

Given Japan's limited supply of energy resources, the country's electric power companies are endeavoring to develop an optimal combination of power sources, including hydro, thermal, and nuclear power (Figure 2).

[Figure 2]

Hydroelectric, geothermal, and nuclear power provide a base load supply in Japan, can generate around 800 GWh electricity per hour[11]. Hydroelectric power is able to provide both a

renewable electricity sources are also set to enter the market in the fiscal year of 2019 (From April 2019 to March 2020).

8 The share is calculated by dividing the trading value of the spot market into the total trading value in JEPX in 2017.

9 Since the second phase of the *5th* electricity market reforms began in 2016, Japan's electricity market was opened up to competition. The ultimate objective of this reform was to separate the transmission, distribution, and generation of electricity in Japan by 2020.These electricity market reforms aimed to meet the following three government objectives: to secure a stable supply of electricity, to lower electricity prices, and to provide greater choice for consumers through competition amongst business entities (Wakiyama and Kuriyama, 2018).

10 For instance, the market share of Nord Pool Spot is 77% in the Nordic market in 2012 (Nord Pool Spot; 2012).

11 Calculated by the summation of total electricity supply in the hydroelectric, geothermal, and nuclear power sectors (Hokkaido EPCO, Tohoku EPCO, Kyoto EPCO, Chubu EPCO, Hokuriku EPCO, Kansai EPCO, Chugoku EPCO, Shikoku, EPCO, Kyushu EPCO).

stable electricity supply and stable generation cost over the long term, while Japan has almost run out of potential sites for constructing large-scale hydroelectric facilities. Nuclear power generation had also retained an important position in Japan's combination of power sources, but this changed following the accident that occurred at the Fukushima Daiichi Nuclear Power Station in 2011. Thermal power includes coal and LNG power plants, which are major power sources for mid-range load supply. However, thermal power is usually liked to global environmental concerns, such as the discharge of CO_2 and other pollutants. Due to their small scale of generation in Japan, renewable energy sources, such as wind and solar power, are used to respond to peak demand fluctuations[12].

On the other hand, the Japanese government issued the "Energy Mix" of FY2030 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). In fact, the Japanese government started to encourage the development of renewable energies over a decade ago by implementing various promotion policies. For instance, the Renewable Portfolio Standards (RPS) system was introduced in 2002. This policy aimed to take measures relating to the use of new energy by electricity retailers in order to enhance the stability of Japan's energy supply. Annual targets regarding the utilization of electricity from renewable energy by electric retailers were also established, aiming to increase this figure from 7,320 GWh in 2003 to 16,000 GWh by 2014. However, despite the fact that wind power was enlarged by the adoption of RPS, renewable energy electricity generation still accounted for no more than 1.04% of Japan's total electricity generation. Therefore, in July 2012, Japan shifted its renewable energy promotion policy from RPS to Feed-in Tariffs (FIT). This was due to the growing expectation that further renewable energy deployment would replace nuclear as a power source following the Fukushima accident in 2011. The FIT system was designed to stimulate investment in renewable energy generation by guaranteeing the purchase of electricity over the long term. After implementation of the FIT, the generation of solar electricity has increased significantly since 2013. Figure 3 shows the trends in solar and wind energy generation from 2010 to 2017. While only 66,000 GWh of solar electricity was generated in 2012, this amount increased to 550,000 GWh in 2017 (METI[b], 2018). The tariff is adjusted based on the reduction in construction costs driven by technological innovation and increased competition. For example, the initial FIT rate for solar power plants, the capacity of which is larger than 10 KW and less than 2,000 kW, was 40 Yen/kWh when the policy was first enacted in July 2012. However, the rate has been declining year by year. In 2017, the tariff rate of solar power plants was reduced to 21 Yen/kWh.

[12] Solar power only works during the day-time, while wind power is generated during the night.

[Figure 3]

3. Methodology and Data

3.1. Empirical model

In order to estimate the effect of power generation of renewable sources on Japan's electricity market, we adopted the dynamic linear panel-data model as follows:

$$P_{i,j,t} = \alpha + \delta lagP_{i,j,t} + \beta Re_{i,j,t} + \gamma Control_{i,j,t} + \upsilon_{i,j} + \varepsilon_{i,j,t} \tag{1}$$

Here, $P_{i,j,t}$ is the dependent variable that refers to the spot price in the JEPX day-ahead market in area j and hour i at day t[13]. Due to the large price fluctuation in spot prices over one day, we accounted for an intraday seasonality pattern of spot prices by modeling each hour of the day separately. Therefore, we denoted the price defined in Eq.(1) as a vector in each specified hour i at each area j of the day $t,...,T$. $lag\ P_{i,j,t}$ is the lag term of the spot prices, which includes $P_{i-1,j,t}$, $P_{i,j,t-1}$, and $P_{i,j,t-7}$ for separately considering the short run dynamic term by one hour before, one day before, and one week before. $Re_{i,j,t}$ represents the power generation of the solar and wind power industries. $Control_{i,j,t}$ represents the control variables, which include $FITsolar_t$ and $FITwind_t$, the tariff rates provided for renewable powers under the FIT[14] ; $Temperature_{i,j,t}$ is the degree of deviation from the comfortable temperature (18 °C) [15] in each hour; $Interconnection_{i,j,t}$ is the regional power transmission in cross-regional interconnection lines[16]; and $Primay_{i,j,t}$ is the share of power generation of primary energy sources, such as nuclear, hydropower, and thermal power[17]. We also adopt a log-level specification of the

[13] The spot prices are updated 48 times in one day in the Japan's Spot Electricity Market (JEPX). The hourly price data was calculated by averaging the spot prices reported every 30 minutes. For instance, the spot price for 2:00 A.M. equals to the mean value of the prices that were updated at 2:00 A.M. and 2:30 A.M.

[14] $FITsolar_t$ and $FITwind_t$ were set as the tariff rates of the FIT for solar and wind power in each implementation period, respectively. Specifically, the $FITsolar_t$ was set as 24 yen/kWh if the period was between April 2016 and March 2017, 21 yen/kWh between April 2017 and March 2018, and 19 yen/kWh after April 2018. The $FITwind_t$ was set as 22 yen/kWh if the period was between April 2016 and September 2017, 21 yen/kWh between October 2017 and March 2018, and 20 yen/kWh after April 2018.

[15] We set the comfortable temperature as 18 °C, since it is the basic level of warmth required for a healthy and well-dressed person. This standard is recognized by the World Health Organization and is the minimum standard. The form of $Temperature_{i,j,t}$ was represented as absolute value of real $Temperature_{i,j,t}$ minus 18 °C

[16] "Cross-regional interconnection lines" are the transmission lines with 250 kV or more and AC-DC convertors. Each regional service area is firmly connected to these lines by Generation Transmission and Distribution (GT&D) companies (OCCTO[b]).

[17] $Primay_{i,j,t}$ is the share of summation of other forms of energy except of solar and wind power, such likes nuclear, hydropower, and thermal power, divided by electricity demand.

equation, which implies that the estimated coefficient of the logarithm of the renewable power generation represents the elasticity of the day-head spot price in the JEPX market.

3.2. Data

The spot price data of nine Japanese regions were obtained from the homepage of JEPX. The sample period was from April 1, 2016, to June 30, 2018. More specifically, the data includes the transaction value, the nationwide system price, and the spot price in each area. In the market, 48 products are traded every 30 minutes 24 hours a day, and the traded electricity is delivered on the next day[18] (Spot Market, JEPX). The data regarding energy generation in the electricity sector were obtained from nine traditional electric power companies, respectively (Hokkaido EPCO, Tohoku EPCO, Kyoto EPCO, Chubu EPCO, Hokuriku EPCO, Kansai EPCO, Chugoku EPCO, Shikoku, EPCO, Kyushu EPCO). The data contains various electricity power sources, including nuclear, thermal, inflow type hydroelectric, geothermal, biomass, solar, wind, pump-storage type hydroelectric power, and regional power transmission by cross-regional interconnected lines. All of the generation data are organized as hour-level data for each day from April 1, 2016, to June 30, 2018. Information on the tariff rates of FIT were obtained from the Agency for National Resources and Energy (ANRE[a]). The tariff rates have also been cut off by each year, from 2012 to 2017, and these distinctions were used to balance the declining production costs of renewable power sources, including solar PV, wind, hydroelectric, geothermal, and biomass. Temperature data were collected from the Japan Meteorological Agency (JMA). The temperatures were calculated using the average temperature within each area, respectively. The data regarding the utilization rate of the respective power generation facilities was obtained from the Organization for Cross-regional Coordination of Transmission Operator, Japan (OCCTO).

Descriptive Statistics are shown in Table 2. Our hourly sample comprises 177,336 spot prices across 9 areas from April 2016 to June 2018. The average of the spot price was 9.47 yen/kWh during the period. The price gradually improved, and displayed a strong intraday and yearly seasonal pattern (Figure 4 and Figure 5). The price was observed to be higher in the summer and winter, and lower in the spring and autumn during one year. It is also higher during the daytime, with the exception of the noon break time[19].

[Table 2]

[18] A single-price auction system is used in the market. Each bid is made for a combination of price and quantity of each product. The price and contract quantity are decided at the point of the intersection where the buying and selling conditions comply with each other.

[19] The yearly seasonality pattern of the spot price in Japan is derived from the high share of air conditioning using during the summer and winter time, while the intraday seasonality pattern is deemed to change in line with the production activity during the daytime.

[Figure 4]

[Figure 5]

Japan's average hourly electricity use is 7,604 MWh, while the maximum value of electricity demand is approximately 26,569 MWh, which is almost four times the mean value. Figure 6 shows the hourly electricity demand in a day. The peak-demand period of electricity in Japan is from 9:00 A.M. to 20:00 P.M., which mirrors Japan's working hours. The supply from nuclear power died off after the 2011 earthquake off the Pacific coast of Tohoku[20]. After the incident, energy generation from nuclear power was reduced to 0 TWh in 2014 from 288.2 TWh in 2010, and had only recovered to 32.9 TWh by 2017 (ANRE[b]). During our study period, the average hourly generation of nuclear power was 287.2 MWh, while that of thermal power was 6,089 MWh. As the main power supply in Japan, thermal power covered over 80% of the total electricity demand. On the other hand, the average hourly generation of solar and wind power during the study period were 429.6 MWh and 65.84 MWh, respectively. As shown in Figure 7 and Figure 8, the supply of solar and wind power shows seasonal patterns in each year. Supply generated from solar power was higher in the summer and winter, while the opposite was true for wind power. Figure 9 and Figure 10 represent the hourly trends in the supply of solar and wind power. The generation of solar power shows a Gaussian curve that rises from 5:00 A.M., peaks at 12:00 P.M., and then reduces to zero until 20:00 P.M. On the contrary, wind supply is higher in the night, but lower in the morning. According to Table 3, the average utilization rate of the power generation facilities was 73.75%. The utilization rate is lower than 90% most of the time, and only 2.19% of the samples contained utilization rates that were higher than 90%.

[Figure 6]

[Figure 7]

[Figure 8]

[Figure 9]

[Figure 10]

[20] The earthquake occurred at 14:46 P.M. local time on Friday 11 March, 2011. A total of eleven reactors were automatically shut down following the earthquake and the resulting tsunamis. The accident of Fukushima Daiichi Nuclear Power Station caused a huge regional ecological disaster in Fukushima prefecture, and the impact continues to this day.

[Table 3]

4. Estimated Results

Table 4 reports the results for the impacts of renewable power generation on spot prices in Japan's electricity market. Column (1) lists the baseline estimations for the entire country by adopting equation (1) but eliminating $Control_{i,j,t}$. The estimates include the control variables are shown in columns (2) and (3).

[Table 4]

The lag-terms $P_{i-1,j,t}$, $P_{i,j,t-1}$ and $P_{i,j,t-7}$ are used to illustrate the spot price one hour before, one day before, and one week before. These coefficients are positive and statistically significant in all of the columns, suggesting that the spot price in the JEPX market is strongly dependent on the previous price. $Solar_{i,j,t}$ is negative and statistically significant in all of the columns, which means that increasing solar power generation helps to reduce the electricity spot price in the nationwide market. On the other hand, $Wind_{i,j,t}$ is negative and does not show a statistically significant impact on the spot price. The coefficient of $Solar_{i,j,t}$ is -0.03, suggests that a 1 GWh increase in solar power generation leads to a 0.03% reduction in the spot price.
$FITsolar_t$ and $FITwind_t$ are negative and statistically significant in all of the columns, suggesting that the introduction of the FIT system can significantly reduce the spot price. A 1 yen/kWh increase in the tariff rate for solar power led to a 0.001% reduction in the spot price, while a 1 yen/kWh increase in the tariff rate of wind power caused a 0.004% reduction in the spot price. $Temperature_{i,j,t}$ is positive and statistically significant in all of the columns, indicating that 1 °C of the temperature deviating from comfortable temperature leads to a 0.002% increase in the spot price. $Other\_resources_{i,j,t}$ is positive and statistically significant in all of the columns, meaning that the traditional energy resources lead to an increase in the electricity spot price. $Interconnection_{i,j,t}$ is statistically insignificant in all of the columns, indicating that the electricity transmission of cross-regional interconnected lines does not affect the spot price. Moreover, in order to investigate the interactive relationship between electricity demand and renewable power consumption on spot price, a cross-term was added to Eq (1). Our assumption was that the spot price would increase following a rise in electricity demand as a result of a higher cost of electricity entering into the market.

$$\begin{aligned} P_{i,j,t} =& \alpha + \delta lagP_{i,j,t} + \beta Re_{i,j,t} + \delta Diff\_demand_{i,j,t} + \eta Diff\_demand \times Re_{i,j,t} \\ &+ \gamma Control_{i,j,t} + \upsilon_{i,j} + \varepsilon_{i,j,t} \end{aligned} \quad (2)$$

Here, $Diff\_Demand_{i,j,t}$ is set as a dummy variable that is equal to 1 if the electric energy requirements increase ($Diff\_Demand_{i,j,t}$ - $Diff\_Demand_{i,j,t-1}>0$), and is equal to 0 if the requirements decrease ($Diff\_Demand_{i,j,t}$ - $Diff\_Demand_{i,j,t-1}<0$). The cross-term: $Diff\_Demand_{i,j,t} \times Re_{i,j,t}$ is set to show the interaction between the variation of electricity demand and renewable power generation. β is the coefficient that shows the impacts of renewable power generation on the spot price in situations whereby electricity demand decreases, while $\beta+\eta$ represents the impacts when there is an increase in the electricity demand. The estimates are presented in Column (4) of Table 4. $Diff\_Demand_{i,j,t}$ is positive and statistically significant, showing the spot price increase in line with the higher electricity demand. On the other hand, the cross term *of* $Diff\_Demand_{i,j,t} \times Solar_{i,j,t}$ is positive and statistically significant, meaning that a 1 GWh increase in solar power generation led to a reduction in spot price of 0.021% during the period that electricity demand increased, and led to a reduction in spot price of 0.037% when the electricity demand decreased[21].

In summary, the estimation results show that a 1 GWh generation increase in solar power leads to a 0.03% reduction in the price of the Japanese spot market. However, the same effects were not found in wind power sector. We assume this is because only large-scale renewable power generation plants can exert such an impact on reducing the electricity spot price. As shown in Figure 3, in the year of 2017, the electricity generation of solar power in Japan was almost 10 times that of wind power.

In addition, we assume that regional differences exist in Japan's electricity spot market due to the inadequate available transfer capabilities of cross-regional interconnection lines and the country's unique, two separate power grids system. Spot prices are set at different levels in each region. Therefore, in order to estimate the regional differences on the impacts of renewable power generation in the spot market, we analyzed the regional effects among 9 regional service areas of electric power companies in Japan, respectively[22]. The areas are divided by traditional electric power companies' spheres of influence in Japan (Figure 11)[23].

[Figure 11]

The estimation model can be summarized as follows:

---

21 In order to discuss this interaction more carefully, we have also included a robustness check in Appendix A for other renewable power characteristics such as "the peak-time electricity demand," "utilization of electricity system," and "real electricity demand." The results indicate that increasing renewable power generation leads to a lower reduction in the spot price when electricity demand is increasing.

22 The 9 areas were Hokkaido, Tohoku, Tokyo, Hokuriku, Chubu, Kansai, Chugoku, Shikoku, and Kyushu. Okinawa area was eliminated in this study, since the area operates separate from the Japanese electricity system.

23 These privately-owned, independent, regional electric power companies were established in Japan in 1951 and assumed responsibility for supplying each regional service area (The Federation of Electric Power Companies of Japan), while the Okinawa Electricity Power company was established in 1972.

$$P_{i,j,t} = \alpha + \delta lagP_{i,j,t} + \beta Re_{i,j,t} + \eta Area \times Re_{i,j,t} + \gamma Control_{i,j,t} + \upsilon_{i,j} + \varepsilon_{i,j,t} \qquad (3)$$

Here, the $Area \times Re_{i,j,t}$ is the cross-term of $Area_j$ and $Re_{i,j,t}$, which can be used to capture the impact of renewable power generation on the spot price in each area. β shows the impacts in other areas, except area j, while $\beta+\eta$ represents the regional effects of renewable powers in area j.

The estimation results are shown in Table 5. Columns (1) - (9) present the results in each area, respectively. $Solar_{i,j,t}$ is negative and statistically significant in columns (3), (5), (7), and (8). It is positive and statistically significant in column (9). The results indicate that a 1 GWh increase in solar power generation induces reductions in the spot price of 0.145%, 0.134%, 0.053%, 0.850%, and 0.021% in Tokyo, Chubu, Chugoku, Shigoku, and Kyushu areas, respectively[24]. On the other hand, $Wind_{i,j,t}$ is negative and statistically insignificant in all of the columns.

[Table 5]

The results indicate that regional differences exist in the impact of renewable power generation on Japan's electricity spot prices, but that such differences can be only observed in solar power sector. Some factors are considered to intensify regional difference, such as the scale of regional spot market and the transaction volume of renewable power in the market. We assume that the regional effects are highest in Shikoku area, since the area contains the smallest electricity market in terms of scale.

5. Conclusions

This study examined the impacts of renewable electricity supply on reducing spot prices in JPEX. Our results indicate that the increase in renewable electricity generation has caused a reduction in Japan's spot electricity prices. The results of this study are in line with those concluded by existing research focusing on European countries and United State (Clò et al., 2015; Gelabert et al., 2011; Sensfuβ et al., 2008; Woo et al., 2011). However, we found that the impacts depend on the scale of the installed capacity of the power plants. The introduction of wind power in the spot market still cannot affect spot prices due to its extremely small market share in Japan.

On the other hand, we assume that an increase in electricity demand will reduce the impact

[24] The regional impact is calculated by the sum of the coefficients of $Solar_{i,j,t}$ and $Area \times Solar_{i,j,t}$.

of renewable power in the spot market. Higher demand for electricity induces consumers to choose electricity with higher production costs. The production cost of renewable electricity is lower than nuclear and thermal power, since the use of FIT has been allowed in spot transactions since 2018. This had caused renewable electricity to be traded earlier than other resources in the market. However, along with the increasing demand for electricity, the transaction amount of thermal power has also been increasing in the spot market. An increase in the transaction volume of thermal power indirectly has reduced the impact caused by renewable power. Furthermore, due to the tariff cuts of FIT that have been implemented over recent years, we assume that the influence of thermal power will gradually increase if total module costs of renewable power remain constant.

Moreover, regional differences also exist in Japan's spot market. Due to both the inadequate available transfer capabilities of cross-regional interconnection lines and Japan's unique, two separate power grids system, it is difficult to transfer both renewable electricity and other resources across each region. The impacts of renewable electricity supply on the spot market are also estimated to be affected by these regional differences. We assume that both the scale and the transaction volume of a regional spot market are important factors that can affect the impact of renewable electricity generation on the spot market.

Appendix: Characters of the Electric Energy Requirements

In consideration of the characteristics of renewable resources, renewable powers were usually generated to meet the peak demand for electricity. Therefore, the implications of the results on the impacts made by different indicators of the electric energy requirements $Demand\_characters_{i,j,t}$ can also be captured. These indicators can be separated into three types: increase in electricity demand, peak time, and utilization of power plants.

The indicators are adopted to capture the interaction between electricity demand and renewable energy power generation in the spot market. The general form of the dynamic fixed effect model is as follows:

$$\begin{aligned} P_{i,j,t} =& \alpha + \delta lagP_{i,j,t} + \beta Re_{i,j,t} + \lambda Demand\_characters + \eta Demand\_characters \times Re_{i,j,t} \\ &+ \gamma Control_{i,j,t} + \upsilon_{i,j} + \varepsilon_{i,j,t} \end{aligned} \tag{4}$$

"peak time ($Peak_i$)," "increase in demand ($Diff\_Demand_{i,j,t}$)," and "utilization of power system ($Utilization90_i$)" are used as indicators of the electricity demand ($Demand\_characters_{i,j,t}$), where $Diff\_Demand_{i,j,t}$ is set as a dummy variable that is equal to 1 if $Demand_{i,j,t}$ - $Demand_{i,j,t-1} > 0$, and equal to 0 otherwise.This means that $Diff\_Demand_{i,j,t}$ is equal to 1 when electric energy requirements increase, and equal to 0 when the requirements decrease. $\beta+\gamma$ represents the effects when the requirements increase. $Peak_i$ is the dummy variable that represents the peak demand period in the electricity market. On account of the fact that the "peak demand period" is not officially defined in Japan, we adopted two types of peak time in this study. In the first case, we set the period of peak time ($PeakJEPX_i$) equal to 1 from 13:00 P.M. to 16:00 P.M., and 0 otherwise, based on the definition of peak time in JEPX[25]. Additionally, we also set the peak time dummy equal to 1 from 9:00 A.M. to 17:00 P.M., and 0 otherwise, which coincides with the working time period in Japan ($PeakWork_i$). β shows the impacts on off-peak hours, while $\beta+\eta$ represents the effects on peak hours. $Utilization90_{i,j,t}$ is a dummy variable that equals 1 if $Utilization_{i,j,t} \geq 90\%$, and 0 otherwise[26]. The utilization rate is defined as the electricity capacity which can be used to generate electricity divided by the total electricity capacity. A higher utilization rate means a more strained relationship between power supply and demand. $\beta+\eta$ represents the effects of renewable power generation on the spot price when facing an electricity shortage.

[25] In JEPX the Day Ahead Peak Time is defined as 13:00-16:00 P.M.: Homepage JEPX's: http://www.jepx.org/english/.

[26] The standard reserve margin is concluded between 8% - 10% criterion by OCCTO, Japan: https://www.occto.or.jp/iinkai/chouseiryoku/2015/files/cyousei_01_06_01.pdf (In Japanese).

The estimation results are shown in Table A1. *Diff_Demand* × $Solar_{i,j,t}$ is positive and statistically significant in column (5), illustrating that a 1 GWh increase in solar power generation will lead to a 0.082% (Calculated by -0.105***+0.023***) decrease in the spot price when electric energy requirements increase. $Solar_{i,j,t}$ is negative and statistically significant, while *PeakJEPX* × $Solar_{i,j,t}$ is positive and statistically significant in column (2). This result shows that the peak time effect of solar generation on spot price is -0.045 during the peak time period from 13:00 P.M. to 16:00 P.M.. The result indicates that a 1 GWh increase in solar generation leads to a 0.045% decrease in the spot price during the peak time period[27]. On the other hand, as shown in column (3), when the peak time is set as working times from 9:00 A.M. to 17:00 P.M., the peak time effect on the spot price is -0.074% (calculated by -0.193***+0.119***). The coefficients of *Utilization90* × $Solar_{i,j,t}$ are positive and statistically significant in column (4), indicating that the elasticity of the impact of solar generation on spot price is -0.061% (clculated by -0.096***+0.035***) when the utilization rate is larger than 90%.

[Table A1]

The results illustrate that electric energy requirements are important factor in affecting the impact of solar generation on the JEPX market. Our results indicate that higher electric energy requirements will result in lower impacts of the introduction of renewable power into the market.

[27] The period effects are calculated by the sum of the coefficients of **Solar**$_{i,j,t}$ and **PeakJEPX × Solar**$_{i,j,t}$.

Table 1: Three types of power resources in Japan

	Base Load Supply	Mid-range Load Supply	Peak Load Supply
Cost of operation	Low cost	Middle cost	High cost
Power-output fluctuation characteristics	Unable to fluctuation	Able to fluctuation	Easy to fluctuation
Power sources	Hydroelectric Geothermal Nuclear	Coal LNG and Other Gas	Oil-fired Pumped-storage Solar Wind Biomass

Table 2: Descriptive Statistics

Variables	Unit	N	Mean	Std. Dev.	Min	Max
$P_{i,j,t}$	Yen/kWh	177,336	9.469	4.033	2	57.98
$Demand_{i,j,t}$	MWh	177,336	7,604	5,576	195	26,569
$Nuclear_{i,j,t}$	MWh	177,336	287.2	673.6	0	4,117
$Thermal_{i,j,t}$	MWh	177,336	6,089	4,499	136	21,236
$Hydroelectric_{i,j,t}$	MWh	177,336	799.8	650.6	6	4,751
$Solar_{i,j,t}$	MWh	177,336	429.6	900.1	0	6,656
$Wind_{i,j,t}$	MWh	177,336	65.84	104.2	0	851
$Real\ temperature_{i,j,t}$	°C	177,336	14.69	8.861	-12.87	35.35
$FIT\ Solar_t$	Yen/kWh	177,336	22.11	1.791	19	24
$FIT\ Wind_t$	Yen/kWh	177,336	21.56	0.684	20	22
$Interconnection_{i,j,t}$	MWh	177,336	-107.0	1289	-4961	5097
$Utilization_{i,j,t}$	%	171,846	73.75	9.375	41	98

Table 3: Descriptive of Utilization

$Utilization_{i,j,t}$	Freq.	Percent (%)	Cum. (%)
< 49	1,041	0.61	0.61
50 - 59	13,092	7.61	8.22
60 - 69	39,967	23.26	31.48
70 - 79	65,327	38.02	69.50
80 - 89	48,661	28.31	97.81
≥ 90	3,758	2.19	100

Table 4: The impact of renewable power generation in spot market

$P_{i,j,t}$	(1)	(2)	(3)	(4)
$P_{i-1,j,t}$	0.769***	0.768***	0.761***	0.739***
	(0.013)	(0.013)	(0.013)	(0.013)
$P_{i,j,t-1}$	0.104***	0.104***	0.099***	0.127***
	(0.006)	(0.006)	(0.006)	(0.006)
$P_{i,j,t-7}$	0.114***	0.113***	0.112***	0.102***
	(0.004)	(0.004)	(0.004)	(0.004)
$Solar_{i,j,t}$	-0.030***	-0.031***	-0.030***	-0.037***
	(0.003)	(0.003)	(0.003)	(0.004)
$Wind_{i,j,t}$	-0.012	-0.016	-0.022	-0.010
	(0.016)	(0.016)	(0.015)	(0.017)
$FIT\ Solar_t$		-0.001	-0.001*	-0.001*
		(0.001)	(0.001)	(0.001)
$FIT\ Wind_t$		-0.003**	-0.004***	-0.004**
		(0.001)	(0.001)	(0.001)
$Temperature_{i,j,t}$			0.002***	0.002***
			(0.000)	(0.000)
$Other\_Resources_{i,j,t}$			0.038***	0.034***
			(0.010)	(0.009)
$Interconnection_{i,j,t}$			0.001	0.001
			(0.002)	(0.002)
$Diff\_Demand_{i,j,t}$				0.027***
				(0.003)
$Diff\_Demand \times Solar_{i,j,t}$				0.016***
				(0.004)
$Diff\_Demand \times Wind_{i,j,t}$				-0.030**
				(0.015)
Constant	0.042**	0.130***	0.141***	0.136***
	(0.017)	(0.039)	(0.041)	(0.040)
N	175,824	175,824	175,824	175,824
R^2_{within}	0.868	0.868	0.869	0.872

Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: The robust option was used on all of the models. Season dummy variables were used in all of the columns. The fixed effects method was selected for all of the models, since the results of the Hausman test < 0.05.

Table 5: The regional effects of renewable power generation in spot market

$P_{i,j,t}$	(1) Hokkaido	(2) Tohoku	(3) Tokyo	(4) Hokuriku	(5) Chubu	(6) Kansai	(7) Chugoku	(8) Shikoku	(9) Kyushu
$P_{i-1,j,t}$	0.760***	0.761***	0.760***	0.760***	0.760***	0.760***	0.760***	0.757***	0.760***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)
$P_{i,j,t-1}$	0.099***	0.099***	0.099***	0.099***	0.099***	0.099***	0.099***	0.099***	0.099***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
$P_{i,j,t-7}$	0.112***	0.112***	0.112***	0.112***	0.112***	0.112***	0.112***	0.113***	0.112***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
$Solar_{i,j,t}$	-0.030***	-0.030***	-0.030***	-0.033***	-0.030***	-0.028***	-0.028***	-0.032***	-0.035***
	(0.003)	(0.003)	(0.003)	(0.004)	(0.003)	(0.003)	(0.003)	(0.003)	(0.004)
$Wind_{i,j,t}$	-0.017	-0.022	-0.023	-0.025	-0.022	-0.022	-0.024	-0.025	-0.024
	(0.017)	(0.014)	(0.015)	(0.016)	(0.015)	(0.015)	(0.016)	(0.015)	(0.016)
$FIT\ Solar_t$	-0.001*	-0.001*	-0.001**	-0.001*	-0.001*	-0.001*	-0.001*	-0.002**	-0.001*
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)
$FIT\ Wind_t$	-0.004***	-0.004***	-0.004***	-0.004***	-0.004***	-0.004***	-0.004***	-0.004**	-0.004***
	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.001)	(0.002)	(0.001)
$Temperature_{i,j,t}$	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***	0.002***
	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)	(0.000)
$Other\_Resources_{i,j,t}$	0.039***	0.038***	0.034***	0.037***	0.037***	0.041***	0.036***	0.019*	0.040***
	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.010)	(0.011)	(0.010)
$Interconnection_{i,j,t}$	0.001	0.001	0.002	0.001	0.002	0.001	0.001	0.002	0.001
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
$Area \times Solar_{i,j,t}$	0.016	0.000	-0.115***	0.008	-0.104***	-0.013	-0.025**	-0.818***	0.014**
	(0.022)	(0.008)	(0.035)	(0.006)	(0.036)	(0.008)	(0.011)	(0.161)	(0.005)
$Area \times Wind_{i,j,t}$	-0.071**	-0.000	-0.236	0.018	-0.041	0.006	0.029	0.549	0.048
	(0.034)	(0.028)	(0.299)	(0.047)	(0.085)	(0.073)	(0.034)	(0.601)	(0.029)
Constant	0.144***	0.141***	0.152***	0.144***	0.146***	0.142***	0.145***	0.162***	0.144***
	(0.041)	(0.041)	(0.040)	(0.041)	(0.041)	(0.041)	(0.041)	(0.041)	(0.041)
N	175,824	175,824	175,824	175,824	175,824	175,824	175,824	175,824	175,824
R^2_{within}	0.869	0.869	0.869	0.869	0.869	0.869	0.869	0.869	0.869

Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: The robust option was used on all of the models. Season dummy variables were used in all of the columns. The fixed effects method was selected for all of the models, since the results of the Hausman test < 0.05.

Table A1: The impacts of interrelation between electric requirements and renewable power generation in spot market

$P_{i,j,t}$	(1) Nationwide	(2) PeakJEPX	(3) PeakWork	(4) Utilization≥90	(5) Diff_Demand	(6) Demand
$P_{i-1,j,t}$	0.761***	0.761***	0.764***	0.760***	0.751***	0.710***
	(0.013)	(0.013)	(0.013)	(0.013)	(0.013)	(0.012)
$P_{i,j,t-1}$	0.101***	0.100***	0.098***	0.100***	0.105***	0.094***
	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)	(0.006)
$P_{i,j,t-7}$	0.112***	0.112***	0.110***	0.112***	0.111***	0.098***
	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)	(0.004)
$Solar_{i,j,t}$	-0.095***	-0.112***	-0.193***	-0.096***	-0.105***	-0.655***
	(0.009)	(0.009)	(0.020)	(0.009)	(0.009)	(0.142)
$Wind_{i,j,t}$	-0.030*	-0.038*	0.003	-0.027	-0.017	-0.274
	(0.018)	(0.020)	(0.016)	(0.018)	(0.018)	(0.368)
$FIT\ Solar_t$	-0.034**	-0.035**	-0.038**	-0.043***	-0.041**	-0.095***
	(0.016)	(0.016)	(0.016)	(0.016)	(0.016)	(0.018)
$FIT\ Wind_t$	-0.072**	-0.072**	-0.072**	-0.068**	-0.042	-0.082**
	(0.032)	(0.032)	(0.033)	(0.032)	(0.033)	(0.033)
$Temperature_{i,j,t}$	0.010***	0.009***	0.009***	0.010***	0.008***	-0.009***
	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)	(0.002)
$Primary_{i,j,t}$	0.027***	0.025**	0.032***	0.027***	0.024***	0.013
	(0.010)	(0.010)	(0.010)	(0.010)	(0.009)	(0.008)
$Interconnection_{i,j,t}$	0.003	0.003	0.002	0.004	0.003	-0.000
	(0.006)	(0.006)	(0.005)	(0.006)	(0.006)	(0.005)
$PeakJEPX \times Solar_{i,j,t}$		0.067***				
		(0.011)				
$PeakJEPX \times Wind_{i,j,t}$		0.048				
		(0.054)				
$PeakWork \times Solar_{i,j,t}$			0.119***			
			(0.021)			
$PeakWork \times Wind_{i,j,t}$			-0.090*			
			(0.046)			
$Utilization90_{i,j,t}$				0.008**		
				(0.004)		
$Utilization90 \times Solar_{i,j,t}$				0.035***		
				(0.007)		
$Utilization90 \times Wind_{i,j,t}$				-0.025		
				(0.036)		
$Diff\_Demand_{i,j,t}$					0.014***	
					(0.002)	
$Diff\_Demand \times Solar_{i,j,t}$					0.023***	
					(0.006)	
$Diff\_Demand \times Wind_{i,j,t}$					-0.025*	
					(0.014)	
$Demand_{i,j,t}$						0.233***
						(0.021)
$Demand \times Solar_{i,j,t}$						0.060***
						(0.015)
$Demand \times Wind_{i,j,t}$						0.023
						(0.042)
Constant	0.364***	0.370***	0.380***	0.380***	0.303***	-1.171***
	(0.091)	(0.091)	(0.092)	(0.091)	(0.093)	(0.208)
N	175,824	175,824	175,824	175,824	175,824	175,824
R^2_{within}	0.870	0.870	0.871	0.870	0.871	0.876

Standard errors in parentheses. * $p < 0.1$, ** $p < 0.05$, *** $p < 0.01$

Note: The robust option was used on all of the models. Season dummy variables were used in all of the columns. The fixed effects method was selected for all of the model, since the results of the Hausman test < 0.05.

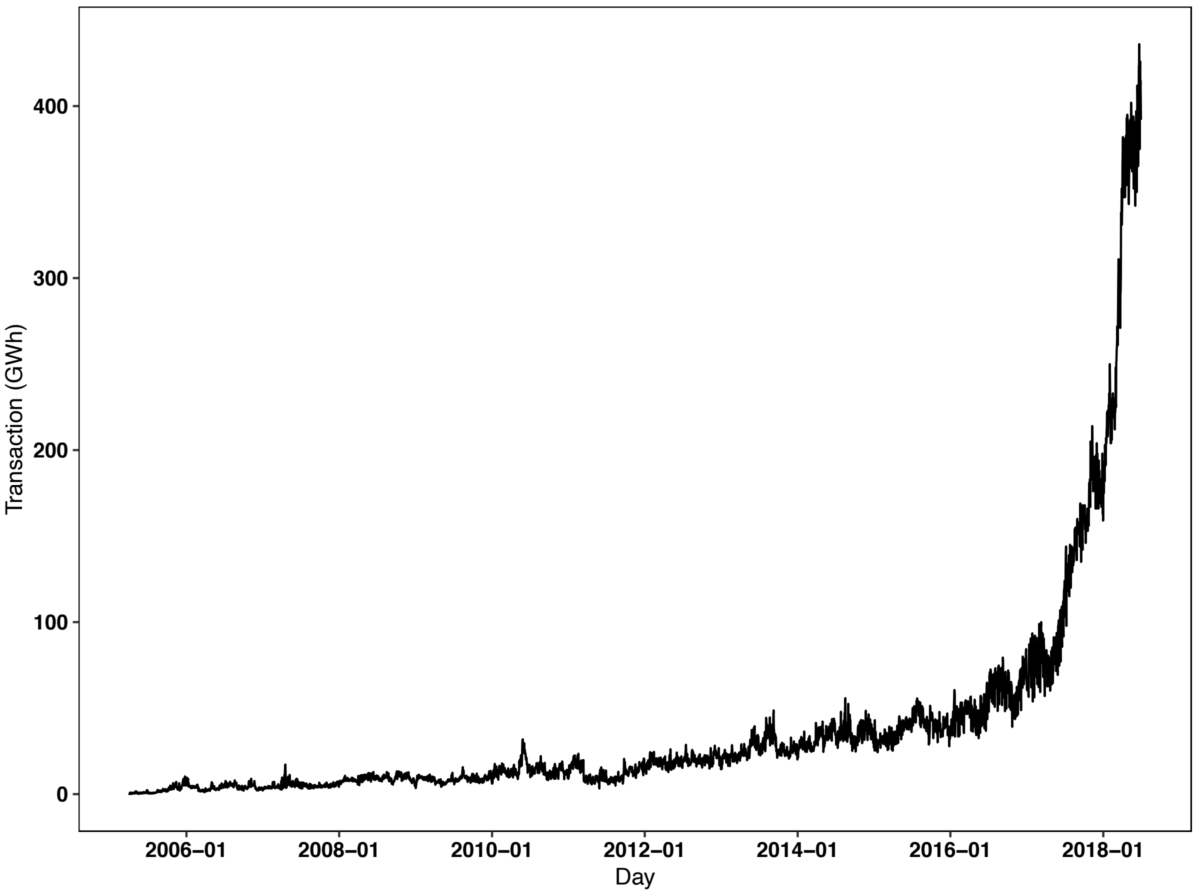

Figure 1: Trend in daily transaction volumes in spot market (2005-2018)

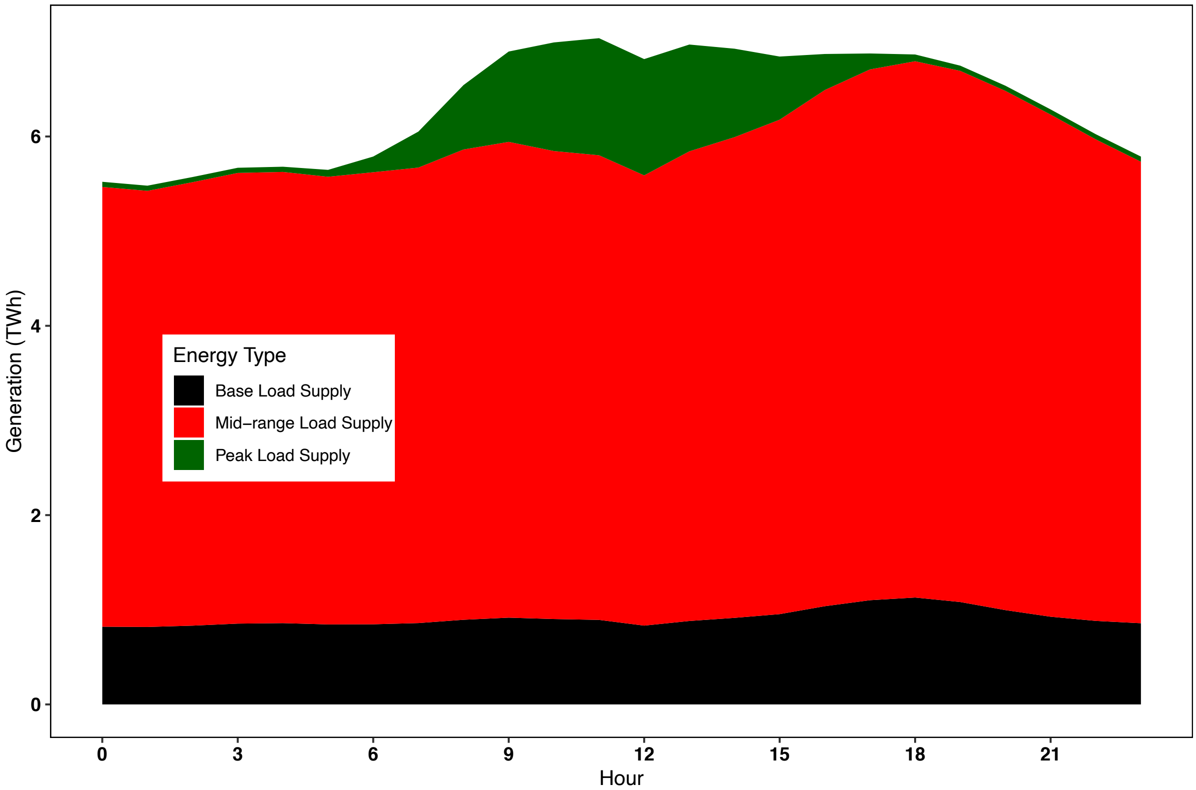

Figure 2: Combination of power sources in Japan

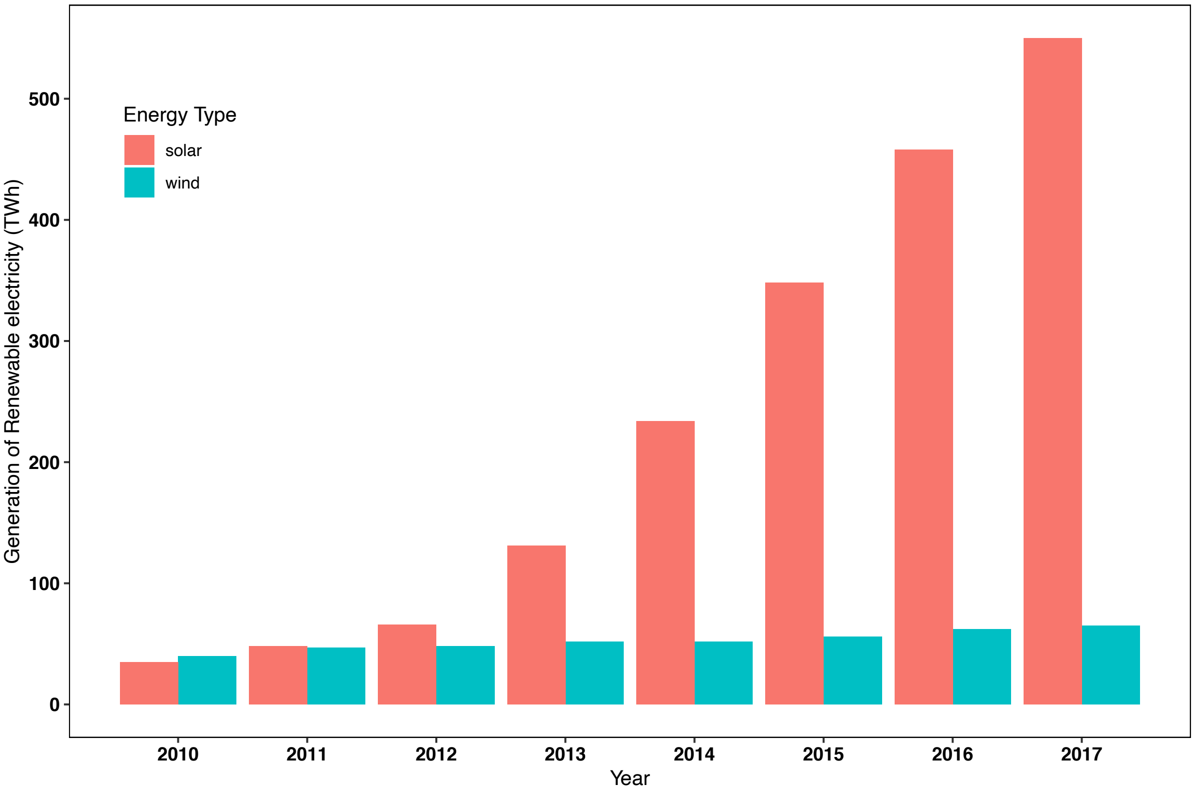

Figure 3: Trend in annual electricity generation of renewable energy projects (2010-2017)

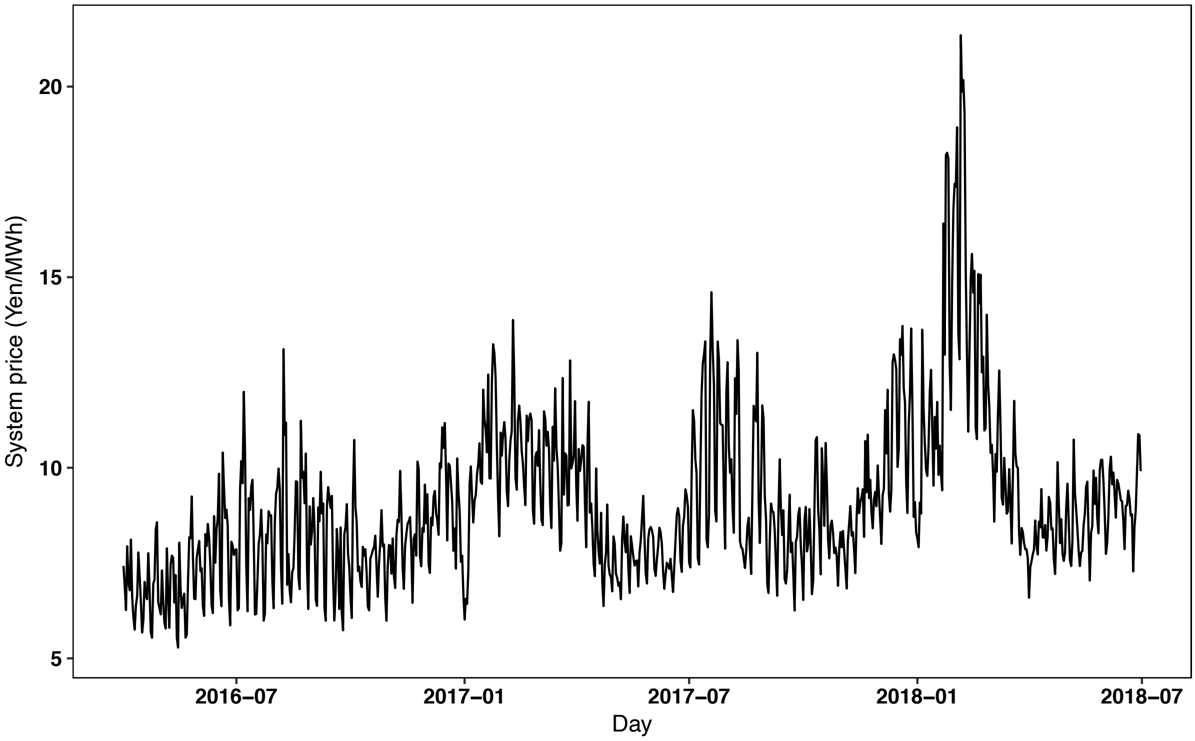

Figure 4: Trend in daily system price in spot market

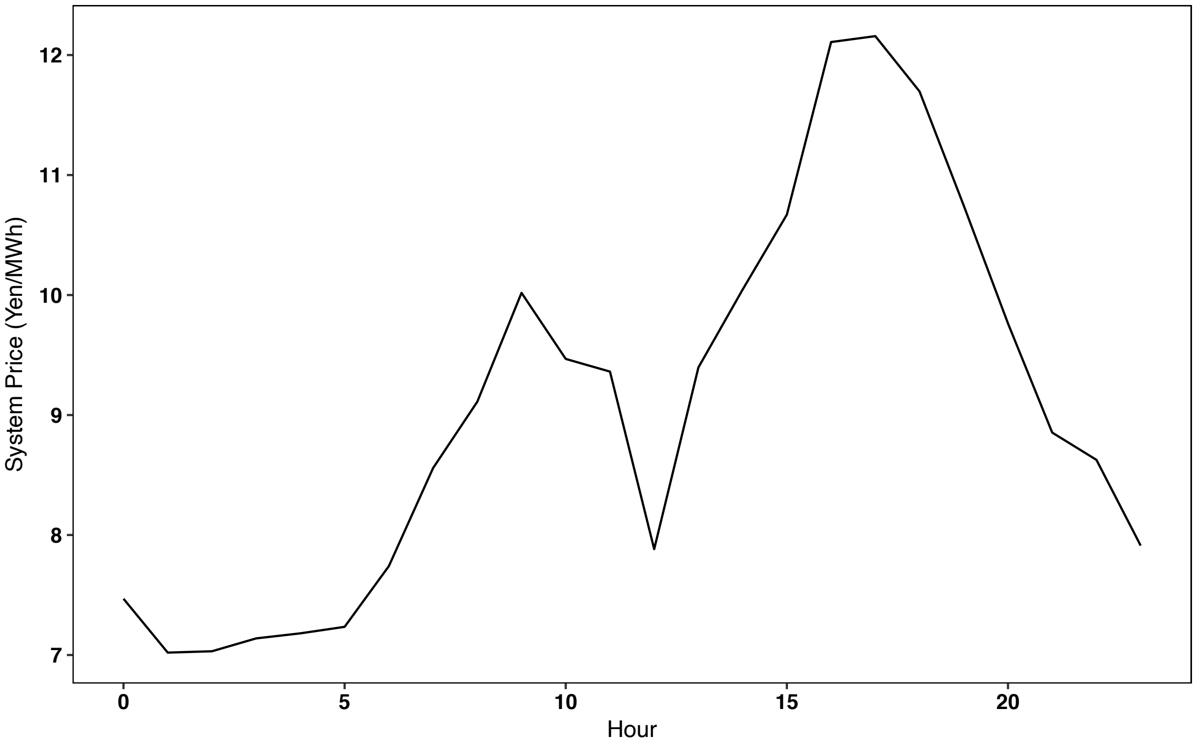

Figure 5: Trend in hourly system price in spot market

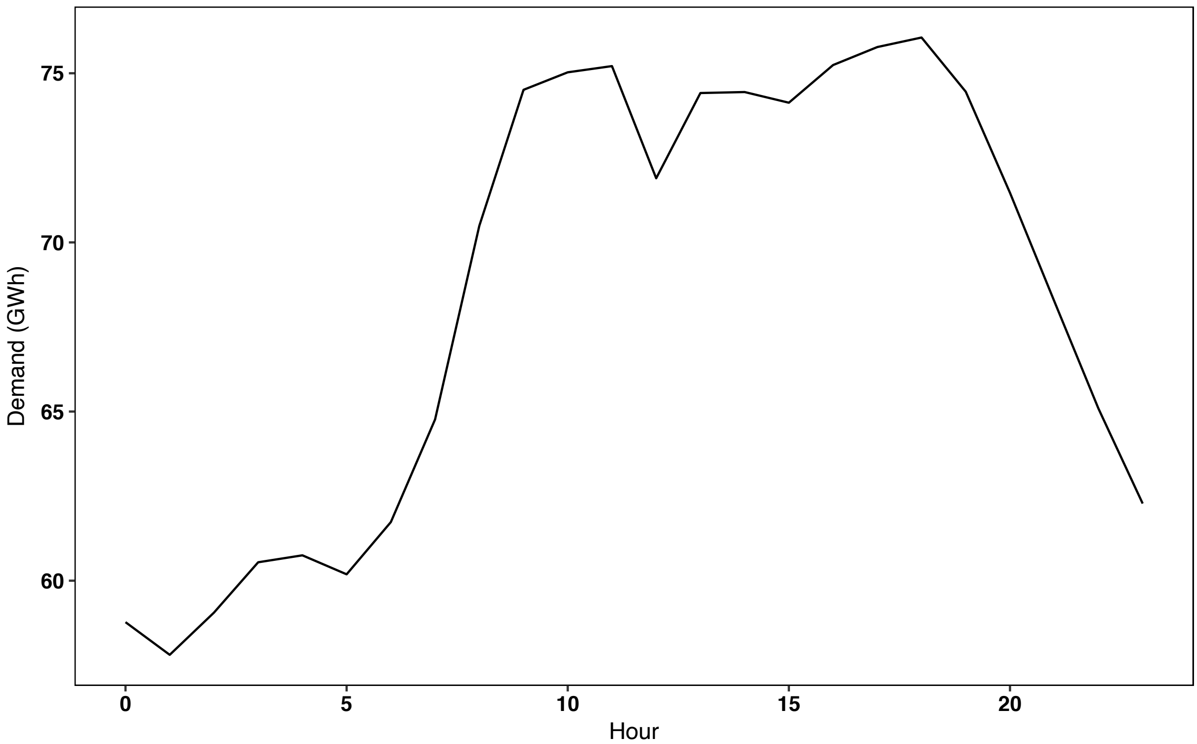

Figure 6: Trend in hourly electricity demand

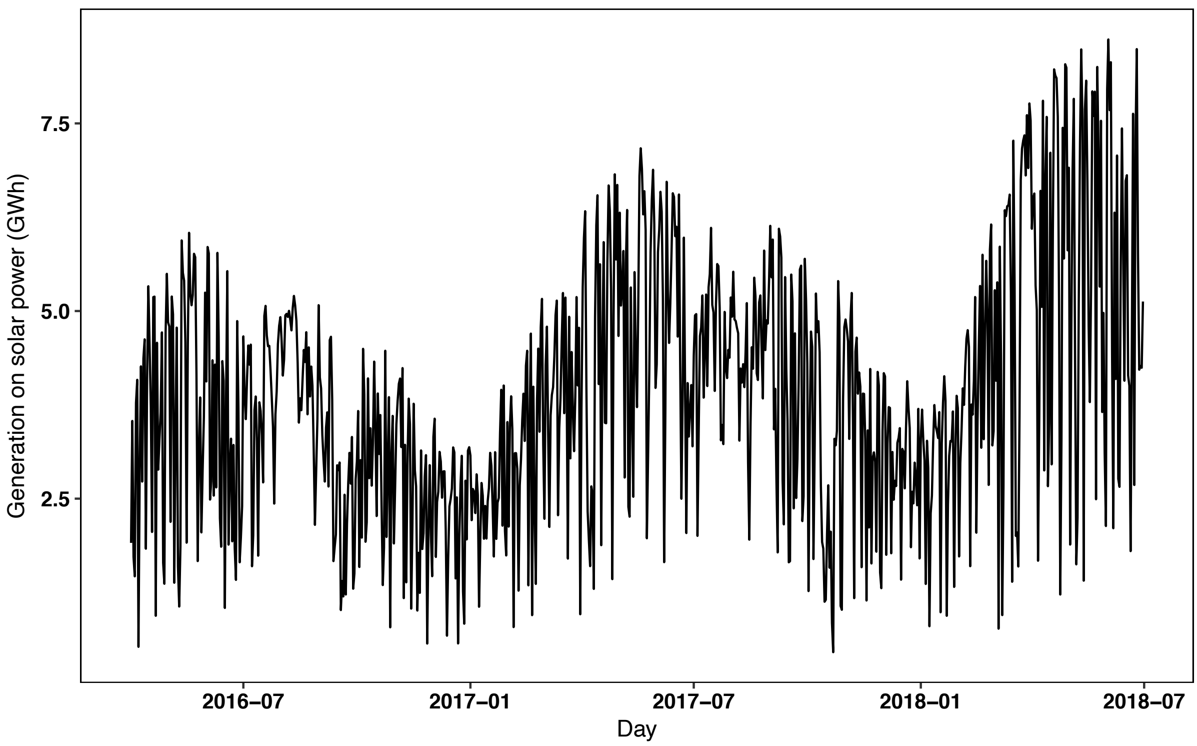

Figure 7: Trend in daily solar power generation (2016-2018)

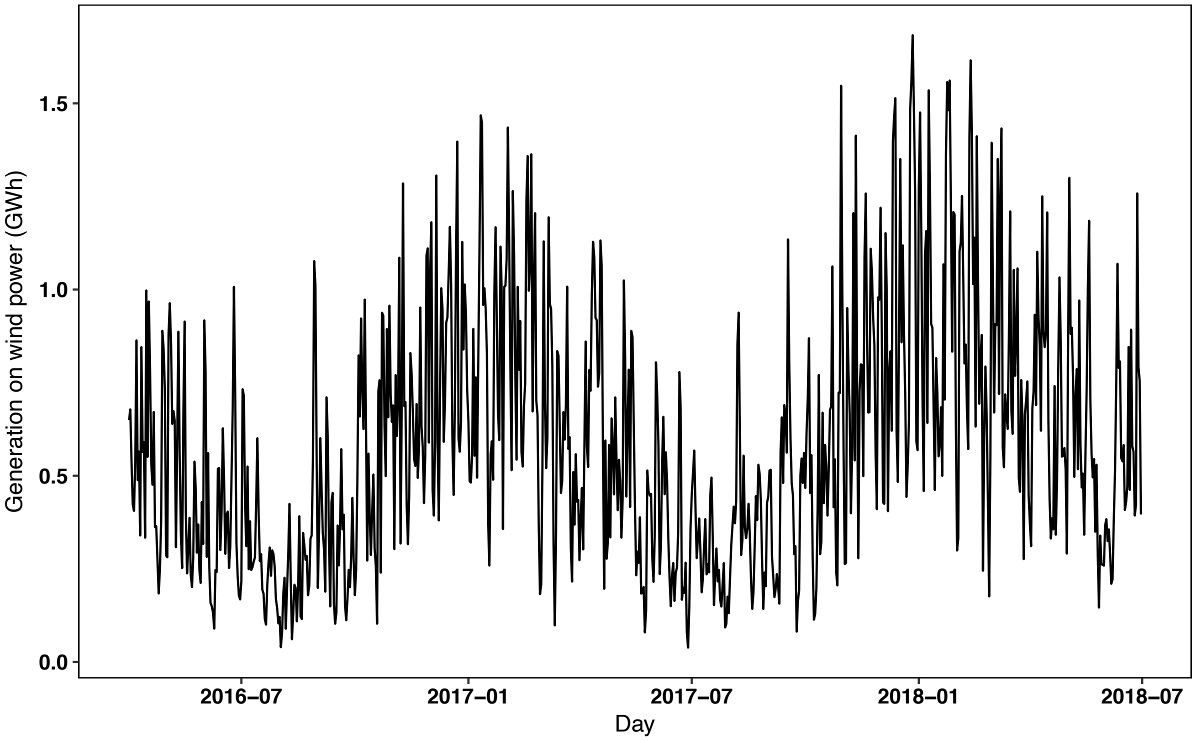

Figure 8: Trend in daily wind power generation (2016-2018)

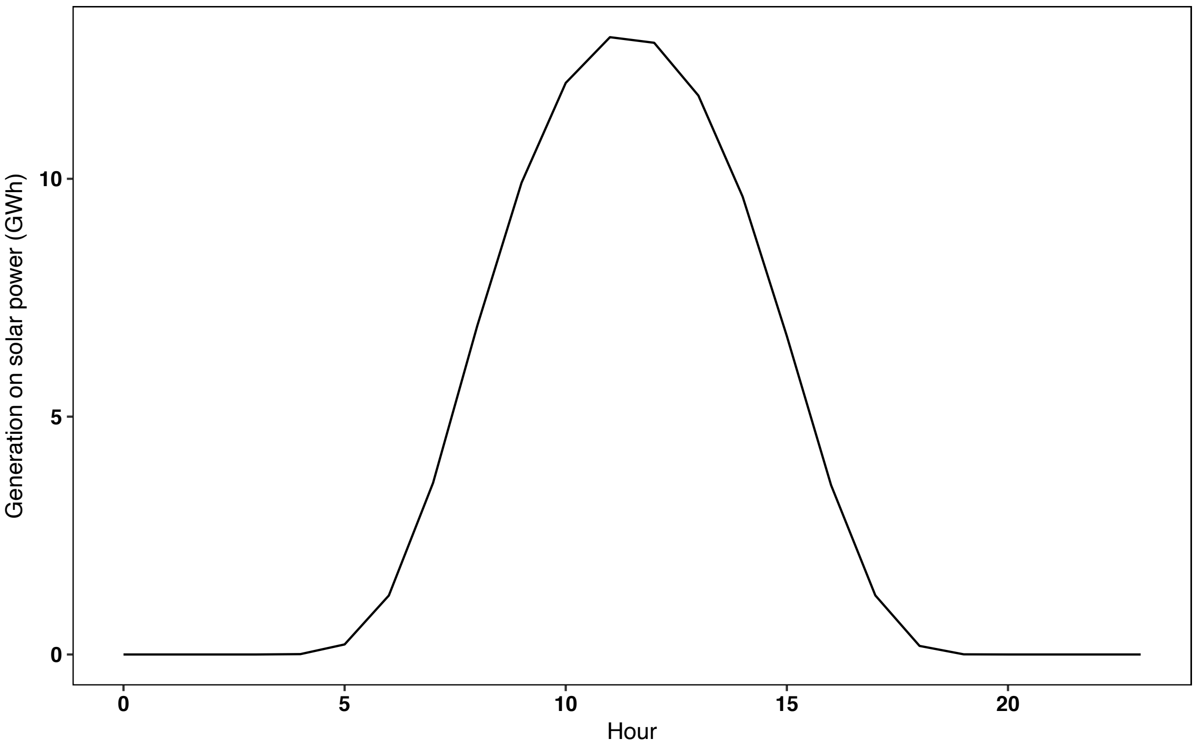

Figure 9: Trend in hourly solar power generation

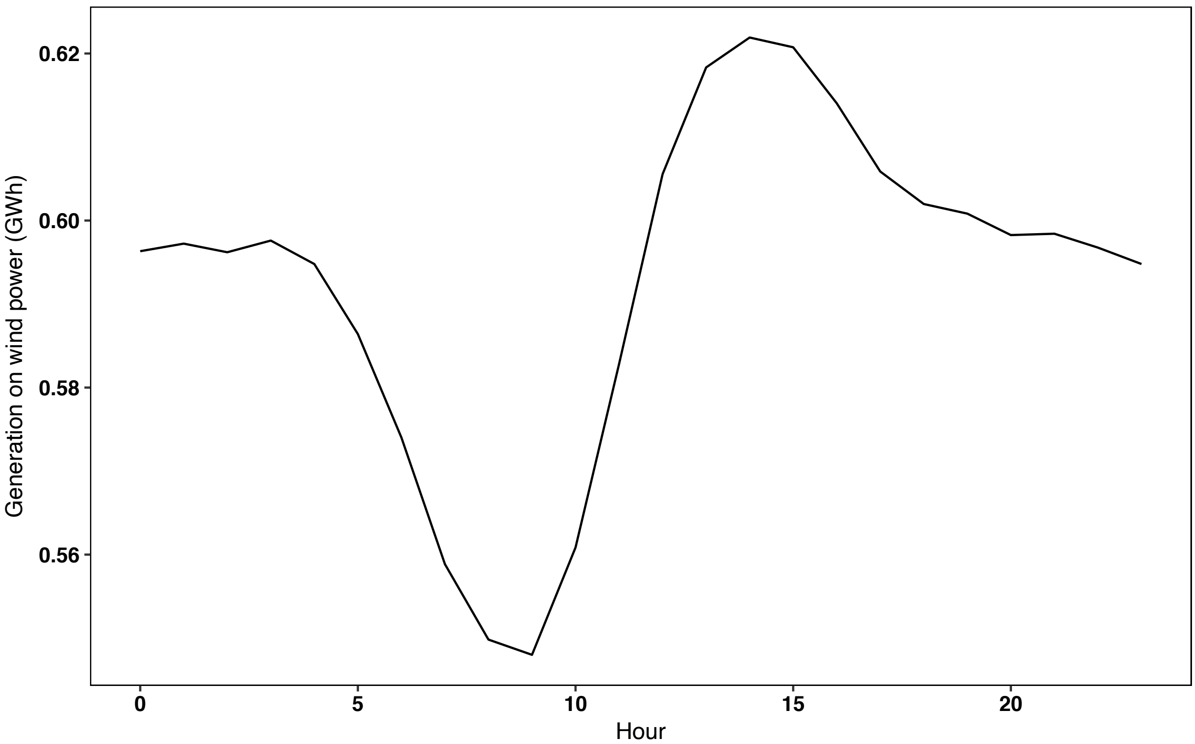

Figure 10: Trend in hourly wind power generation

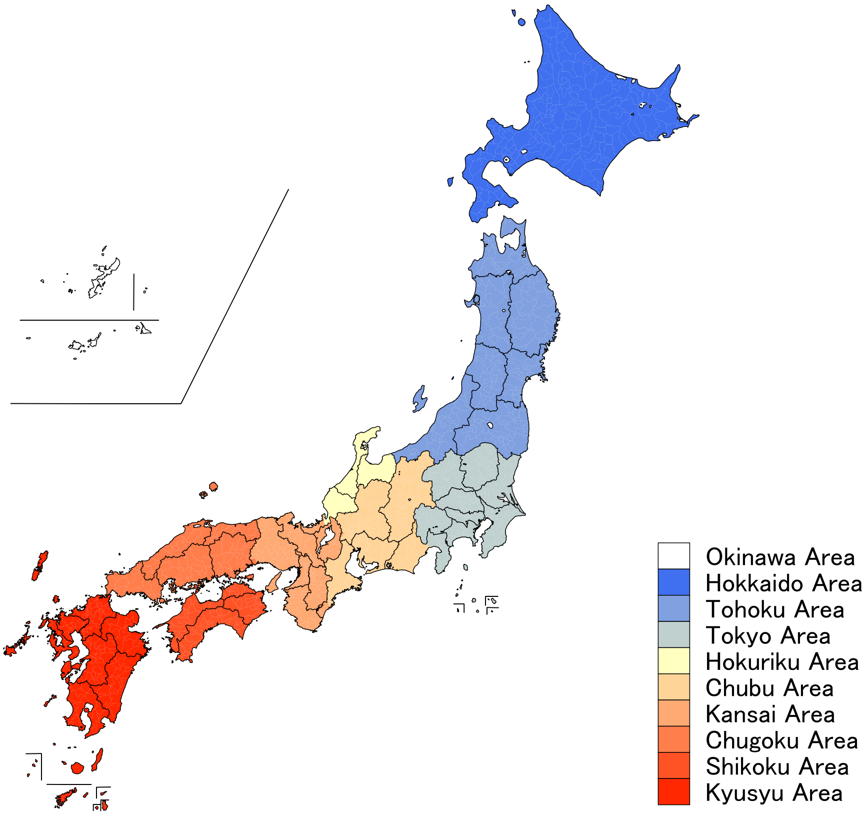

Figure 11: 9 regional service areas of electricity power companies in Japan

References

ANRE[a], Purchase price and period in the past. Home, Policy, Energy saving and new energy, New energy, renewable energy, Feed-in tariff system. http://www.enecho.meti.go.jp/category/saving_and_new/saiene/kaitori/kakaku.html (in Japanese, retrieved September 10, 2018)

ANRE[b] ,Time series table. Home, Statistics and data, Synthesis of statistics, Aggregate results & estimated results. http://www.enecho.meti.go.jp/statistics/total_energy/results.html#headline2

Clò S., Cataldi, A., Zoppoli, P., 2015. The merit-order effect in the Italian power market: The impact of solar and wind generation on national wholesale electricity prices. Energy Policy 77 (2015) 79-88.

EWEA, 2010. Wind Energy and Electricity Prices. European Wind Energy Association. http://www.ewea.org/fileadmin/ewea$_$documents/documents/publications/reports/MeritOrder.pdf

Gelabert, L., Labandeira, X., Linares, P., 2011. An ex-post analysis of the effect of renewables and cogeneration on Spanish electricity prices. Energy Economics 33 (2011) S59-S65.

Inoue, T., Tanaka, T., 2018. A comparative study of long-term price forecasting methods for the JEPX spot market. Central Research Institute of Electric Power Industry (Report). Y17002, March. (In Japanese)

JMA, 2018. Meteorological data in the past. Home, Data and Information. http://www.data.jma.go.jp/risk/obsdl/index.php (in Japanese, retrieved October 8, 2018)

JEPX[a], 2018. Intraday Market. Home, Trading Information, Spot Market. http://www.jepx.org/english/market/index.html (Retrieved October 10, 2018)

JEPX[b], 2018. Spot Market. Home, Outline of Transaction. http://www.jepx.org/english/outline/index.html (Retrieved October 10, 2018)

METI, 2014. 4th Strategic Energy Plan. Ministry of Economy, Trade and Industry, Home, Policies, Strategic Energy Plan, English provisional translation of Japan's new Strategic Energy Plan.

https://www.enecho.meti.go.jp/en/category/others/basicyen_plan/pdf/4thyen_strategicyen_energyyen_plan.pdf

METI, 2015. Long-term Energy Supply and Demand Outlook. Ministry of Economy, Trade and Industry. http://www.meti.go.jp/english/press/2015/pdf/0716_01a.pdf

METI, 2017. The document of 33rd Expert Meeting for System Design. Ministry of Economy, Trade and Industry.
https://www.emsc.meti.go.jp/activity/emsc_system/pdf/033_06_00.pdf#search=%27JEPX+%E3%82%B7%E3%82%A7%E3%82%A22%25%27 (in Japanese)

METI[a], 2018. Electricity System and Market in Japan. Ministry of Economy, Trade and Industry. https://www.emsc.meti.go.jp/english/info/public/pdf/180122.pdf

METI[b], 2018. Time serious. Agency for Natural Resources and Energy, Homepage, Statistical data, Comprehensive energy data, Aggregate results.
http://www.enecho.meti.go.jp/statistics/total_energy/results.html#headline7

Nakajima, T., 2013. Inefficient and opaque price formation in the Japan Electric Power Exchange. Energy Policy, 55, 329-334.

Nord Pool Spot 2012. The Power of Transparency Annual Report 2012, Nord Pool AS. Retrieved October 10, 2018.

OCCTO[a], Information download. Home, Information system, Download information, CSV download. http://occtonet.occto.or.jp/public/dfw/RP11/OCCTO/SD/LOGIN_login# (in Japanese). Retrieved October 20, 2018.

OCCTO[a], 2018. Outlook of Electricity Supply-Demand and Cross-regional Interconnection Lines: Actual Data for Fiscal Year 2017. Organization for Cross-regional Coordination of Transmission Operators, JAPAN.

OCCTO[c], 2019. Role of OCCTO in the Electricity System Reform. Organization for Cross-regional Coordination of Transmission Operators, JAPAN, Top, English, About OCCTO. https://www.occto.or.jp/en/about_occto/about_occto.html

Ofuji, K., Yamaguchi, N., 2008. Estimation of Bid Curves in Power Exchanges using Time-varying Simultaneous-Equations Models. IEEJ Transactions on Power and Energy, 128, 7, 945-952.

Oka, 2019. Current Status of Nuclear Energy in Japan, Japan Atomic Energy Commission. Keynote lectures, Fukui, Japan.

Sensfuβ, T., Ragwitz. M., Genoese, M., 2008. The merit-order effect: A detailed analysis of the price effect of renewable electricity generation on spot market prices in Germany. Energy Policy, 36, 3086-3094.

Spot Market, JEPX. Home, Outline of Transaction.
http://www.jepx.org/english/outline/index.html (Retrieved March 5, 2019)

The Federation of Electric Power Companies of Japan. History of Japan's Electric Power Industry. Home, Energy&Electricity.
http://fepc.or.jp/english/energy_electricity/history/index.html (Retrieved February 27, 2019)

Tokyo Electric Power Company Holdings[a]. Liberalization of the Electric Power Market. Investor Relations. https://www7.tepco.co.jp/about/ir/know/liberalization-e.html (Retrieved January 14, 2020)

Wakiyama, T., Kuruyama, A., 2018. Assessment of renewable energy expansion potential and its implications on reforming Japan's electricity system. Energy Policy, 115, 302-316.

Woo, C.K., Horowitz, I., Moore, J., Pacheco, A., 2011. The impact of wind generation on the electricity spot-market price level and variance: The Texas experience. Energy Policy, 39, 3939-3944.