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Demand Elasticity Estimation from the Japanese National Electricity Grid Considering Wholesale Market Price

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Abstract: *Estimating the electricity demand elasticity is the fundamental step in designing an efficient demand response program, which includes sophisticated mathematical optimization from the perspectives of consumer satisfaction, dynamic elasticities, supplier strategies, and energy authority policies. This study aims to estimate the static elasticity of electricity demand considering the Japanese wholesale market price and the amount of energy demand in the national grid. The study acquired the data of the Japanese regional grids in the form of supply and demand electricity quantities in GWh from the regional transmission and distribution utilities. The supply quantities are quantified based on the energy production technology, while the demand quantities are obtained in hourly intervals for the period of April 2016 to March 2022. The developed econometric employed the two-stage least square estimation method. From the results, the static electricity demand elasticity is found to be 0.14%, which is justified as the impact of raising the wholesale market price by one ¥/kWh that will affect the national demand quantity a by 0.14% drop, and vice versa.*

Keywords: Electricity Demand; Demand Response; Price Elasticity; Energy Balance.

1. Overview

Global warming and climate change indices have burdened the electric power utilities and policymakers since the electricity sector is the prime contributor to Green House Emissions (GHG). Although electricity is not a primary source of energy, it is the most consumed form of energy. Accordingly, over the last few decades, the electric power grid has evolved into the smart grid, which efficiently performs planning, operation, monitoring, and control activities of the transferred energy from production to the end-user [1]. Based on the global direction to reduce GHG emissions, the smart grid facilitates the planning of energy supply diversifications based on various energy production resources. Although the decline in energy supply production affects the flexibility and resiliency of the electricity sector, as a system, it affects the price as the primal parameter for producer and end-user [2]. In addition, the diversification of various energy resources which has various marginal costs influences the market prices as per the contribution of each energy production source, which is known as the Merit Order Effect (MOE) [3]. As shown in Figure 1, the energy production technologies are sorted based on the marginal prices in ascending order, where the market price is determined at the intersection point between the supply and demand curves. The MOE takes effect when the lower marginal cost energy production technology increases its penetration to the total energy mix, which drives the prices to lower rates [4].

On the other hand, the ability to adjust the demand patterns is a major indicator of flexibility, resiliency, and energy stability, which is consequently reflected in the energy system security and price stability [5]. The general objectives of the Demand Response Programs (DRP) are to reduce the overall energy consumption to obtain mutual interests to suppliers and consumers simultaneously, that enhances system losses as well [6]. In addition, the ability of peak demand shaving to meet the supply without activating expensive energy plans allows energy providers to efficiently maintain their pollution outlooks [7]. DRP has the capability to change the demand patterns to follow pre-identified supply patterns, which enhance the stability of the power systems with special characteristics of high Variable Renewable Energy (VRE) penetration [8]. The DRP are classified into three major categories based on control mechanisms, offered motivations, and decision variables [9]. At the planning stage of all DRP categories, estimating the overall energy demand elasticity is a crucial stage to determine the applicable DRP [10]. The flexibility to shift the fixed demand curve in Figure 1 towards lower quantity which meets lower energy price is described as electricity demand elasticity. The average electricity demand in Figure 1 demonstrates 90 degrees elasticity patterns, which shows perfectly in elastic electricity demand. In [12] a comprehensive demand response model for the residential sector in the Jordanian electricity market has been developed using deep neural networks, where the results revealed a potential demand reduction of 5.4%. In this context, [13] developed a price-based demand response program based on the Japanese wholesale electricity market. The model considered dynamic price elasticity of demand which estimates the energy saving of various DRP categories. The study found that applying the DRP with the Time of Use (ToU) category has the potential to save energy in a range of 2-4% according to the seasonality.

In Japan, over the last two decades, the electricity market has been through an extensive liberalization process. After the establishment of the Japanese Electric Power eXchange (JEPX) as the wholesale electricity spot market, the wholesale electricity price is determined in the auction pool where supplier and demand aggregators submit their biddings and offers for the day-ahead energy delivery [14].

In 2019, the Transmission System Operators (TSO) are allowed to trade in JEPX on behalf of the demand response aggregators in the form of negawatts contracts [15]. The JEPX spot market and national power grid's supply and demand patterns have been selected for this investigation due to the recent intensive deregulation process subjected to JEPX. Although JEPX is one of the

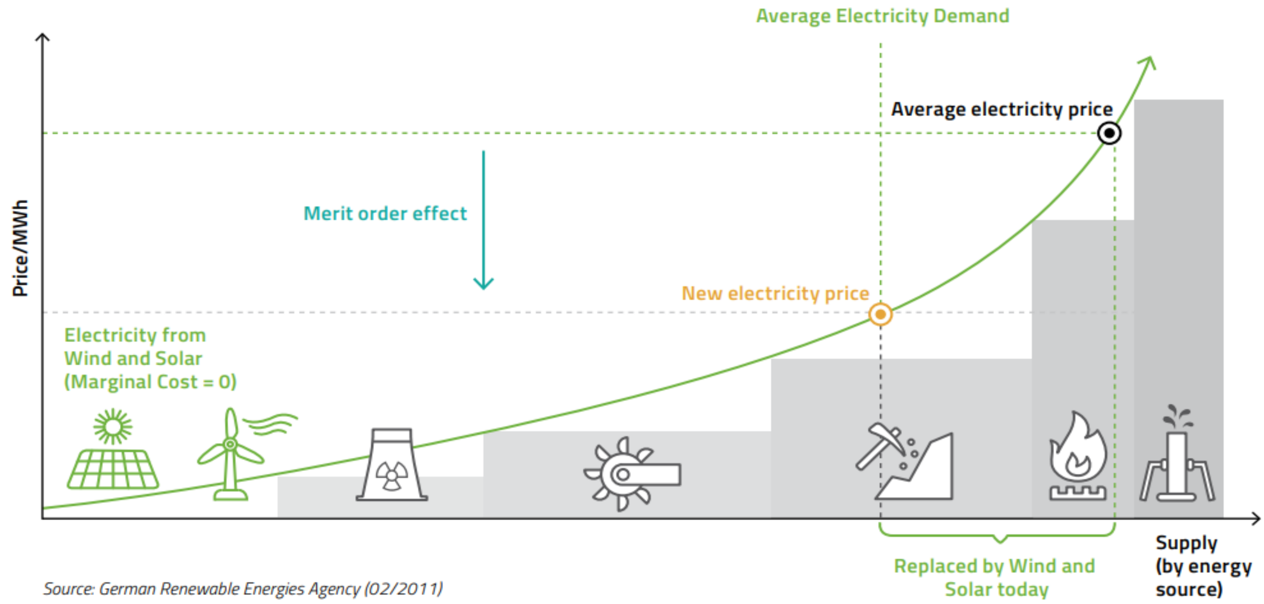

Fig. 1. Conceptual MOE Curve for Various Energy Production Technologies [11].

globally fastest evolving markets, it is lack of the scientific literature. Therefore, this study aims to estimate the elasticity of electricity demand considering the Japanese wholesale market price and the amount of energy demand in the national grid.

Table 1. Data description of electricity supply and demand in the Japanese National Power Grid, average basis (2016–2022).

Category	Unit	Min.	Median	Mean	Max.
Supply	GWh	60	99.17	100.37	164.8
Demand	GWh	60	99.13	100.32	164.8
Nuclear	GWh	1.07	5.462	5.28	9.174
Thermal	GWh	25.12	77	78	129.0
Hydroelectric Power	GWh	2.86	8.08	8.21	16.8
Geothermal	GWh	0.138	0.246	0.25	0.35
Biomass	GWh	0.134	1.04	1.01	2.01
Solar Photovoltaic	GWh	0	0.239	6.94	49.73
Wind Power	GWh	0.01	0.737	0.86	3.11
Hydroelectric Storage	GWh	-17.8	0.121	-0.18	17.3
Interconnection	GWh	-1.11	-0.002	-0.056	0.585
Price	¥/kWh	0.01	8.11	10.09	242

2. Data Collection

The study acquired the quantity of energy supplied and demanded from the regional grids of Japan to form a national database in hourly intervals from April 2016 to the end of March 2022. The hourly supply and demand energy quantities were collected from the nine transmission and distribution electric power utilities of Chubu, Chugoku, Hokkaido, Hokuriku, Kansai, Kyushu, Shikoku, TEPCO, and Tohoku [16-24]. Figure 2 demonstrates the regional electricity grids, where the collected data have consolidated to form singular national grid's database. This database represents the hourly national demand in GWh. Furthermore, the hourly supply per technology is collected for the same period, which forms the hourly energy supply quantity of thermal power generation (Th), nuclear power generation (Nu), hydroelectric power generation (Hy), geothermal power generation (Geo), biomass power generation (Bio), photovoltaic solar power generation (PV), wind power generation (WP), Hydroelectric storage power cycles (HS), and regional interconnection power (Con). On the other hand, the wholesale prices collected from JEPX [25], the data were originally collected in half-hourly intervals, which are processed using the weighted average method to convert the time intervals into hourly [26]. The national data is described in Table 1 in minimum, median, mean, and maximum basis for the case study period.

3. Methodologies

The study aims to analyze the demand elasticity based on the price and supply quantity using the time series data and two stage least square method (2SLS). Since the relation of demand elasticity is based on the price and supply quantity, the time series data using Ordinary Least Square (OLS) falls to identify the correlation [27]. This appears when shifting the demand in correlation to price, which produces completely new equilibrium points. Consequently, to estimate demand elasticity as time series, the demand quantities (Y_t) are used as the dependent variable, which is formulated in equation (1) using the price ($X1_t$) and national supply quantity ($X2_t$) in time series data [27].

$$Y_t = \beta_o + \beta_1 X1_t + \beta_2 X2_t + u_t \tag{1}$$

To resolve the supply endogeneity in correlation to the demand with equilibrium points, two-stage least square estimators are employed, which estimate the national supply first using instrumental variables [28]. Accordingly, the national supply data were estimated in equation (2) using the hourly energy supply quantity of the Th, Nu, Hy, Geo, Bio, PV, WP, HS, and the regional interconnection power (Con).

$$\widehat{X2}_t = \delta_o + \delta_1 Th_t + \delta_2 Nu_t + \delta_3 HY_t + \delta_4 Geo_t + \delta_5 Bio_t + \delta_6 PV_t + \delta_7 Wind_t + \delta_8 HS_t + \delta_9 Con_t + \varepsilon_t \quad (2)$$

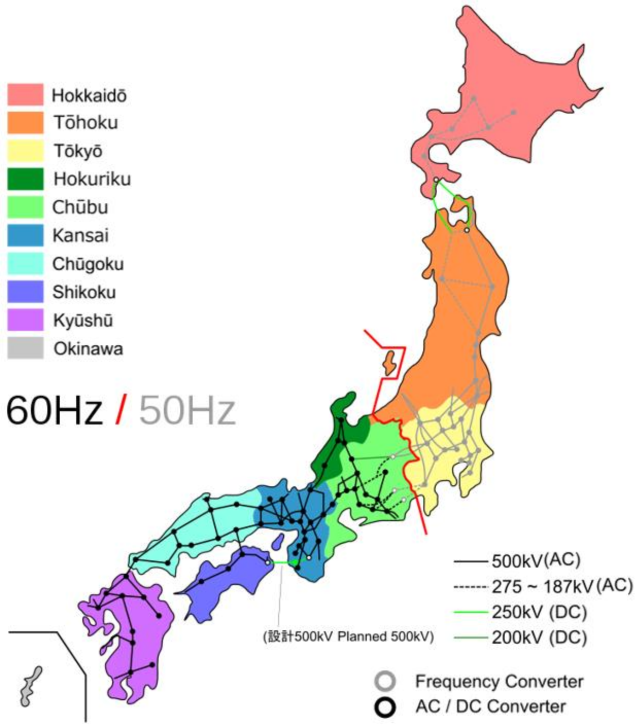

Fig. 2. National Electricity Grid and Regional Utilities.

The estimated second stage of equation (2) was plugged into the structural equation (1), which produced the rearranged reduced form equation (3) as follows:

$$Demand_t = \beta_o + \beta_1 Price_t + \beta_2 \widehat{Supply}_t + u_t \quad (3)$$

From equation (3), the estimated regression coefficients of β_1 *and* β_2 denote the slope difference impact on the demand when one unit of price or supply is added, respectively. However, to calculate the demand elasticity Equation (4) is applied [29]:

$$\eta_D = \beta_1 \frac{\widehat{Price}}{\widehat{Demand}} \quad (4)$$

Where η_D denotes the demand elasticity, $\widehat{Price}$ and $\widehat{Demand}$ are substituted in equation (4) by the mean values of data shown in Table 1. Furthermore, β_1 denotes the price coefficient of the two-stage regression equation.

3.1 Robustness Validation

The consistency of the model is validated on strict orthogonality of the exogeneity assumption as shown in condition (5), where independent variables have at least less than 5% correlation with the error term u [27].

$$E(u_t) = 0, \quad Cov(x_t, u) = 0, \quad t = 1,2, \dots T \quad (5)$$

To validate the instruments variables of equation (2), the null hypothesis shall be rejected at significance level of 0.01 using Hausman Test statistics [30].

4. Results and discussion

The study developed an econometric model using two-stage least square estimation method to estimate the electricity demand elasticity of the Japanese national electricity grid. The hourly electricity demand is visualized in Figure 3, which varies annually with minimum values starting from 60 GWh, which represents the minimum demand hours, and maximum hourly electricity demand that reaches up to 164.8 GWh, which represent the peak demand hours. On the other hand, Figure 4 have scattered the annual hourly electricity demand versus the cross-bonding wholesale market price. In this figure, the demand elasticity from 2016 to 2019 have shown almost typical patterns with maximum price spikes up to 60 ¥/kWh. However, in 2020, the demand versus wholesale price have spiked up to 250 ¥/kWh in considerable spots, which justified in our previous model [28] from supply curve perspective. However, this study has developed a special econometric to further explore the correlation between the wholesale electricity price and the demand using the supply quantity per technology as instrumental variables. The product of this correction is the demand elasticity, which shows the impact of the price change on the electricity quantity demanded. Table 2 shows the regression coefficients β for the supply and wholesale price. To estimate the demand elastisty using equation (4), the mean data of supply and price were substituted from Table 1. Then, the estimated β_1 from table 2 was found to be 0.0139. The obtained demand elasticity from the estimated coefficients are found to be 0.14%. This elaborated in the form of the addition of one ¥/kWh to the hourly wholesale spot price is estimated to decrease the national demand by 0.14%. On the other hand, Figure 5 visualizes the demand elasticity based on the addition of one ¥/kWh to the wholesale market price, which dropped the demand by 14 MWh. The estimated demand elasticity is static planning. However, further analysis is needed to estimate the dynamic demand elasticity, which considers the time series impact at seasonality and hourly levels. The diagnostic tests values of the model are depicted in Table 3, where all the instrumental variables of equation (2) have rejected the null hypothesis to be exogenous at equation (3) with a significance of less than 1%.

5. Conclusion

The study acquired the data of the Japanese regional supply and demand quantities of electricity from the regional transmission and distribution utilities. The supply quantities are quantified based on the energy production technology, while the demand quantities are obtained in hourly intervals. On the other hand, the electricity wholesale prices data are collected from the JEPX for the period of April 2016 to the end of March 2022. The data was processed into a consolidated form of a national database, which was analyzed in this study using the two-stage least square estimation method. The developed econometric employed the supply per technology quantities as instrumental variables to estimate the overall supply quantity before substituting it into the reduced form equation. The results estimated the static electricity demand elasticity which was found to be 0.14%. This is justified as the impact of increasing the

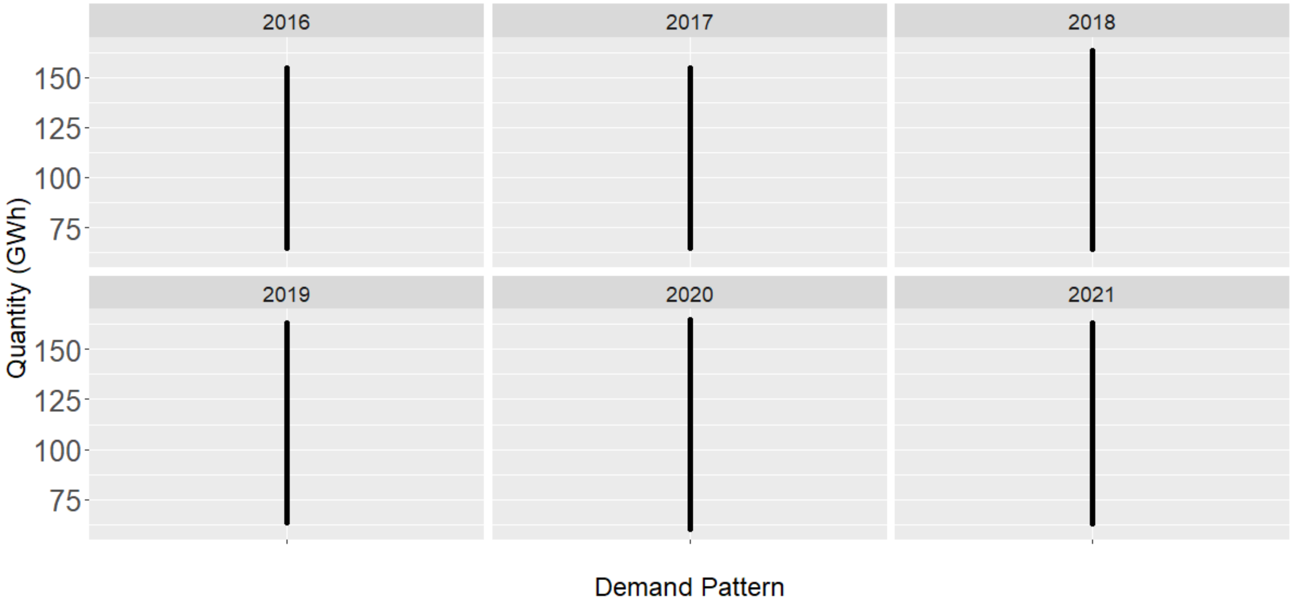

Fig. 3. Yearly National Demand Patterns.

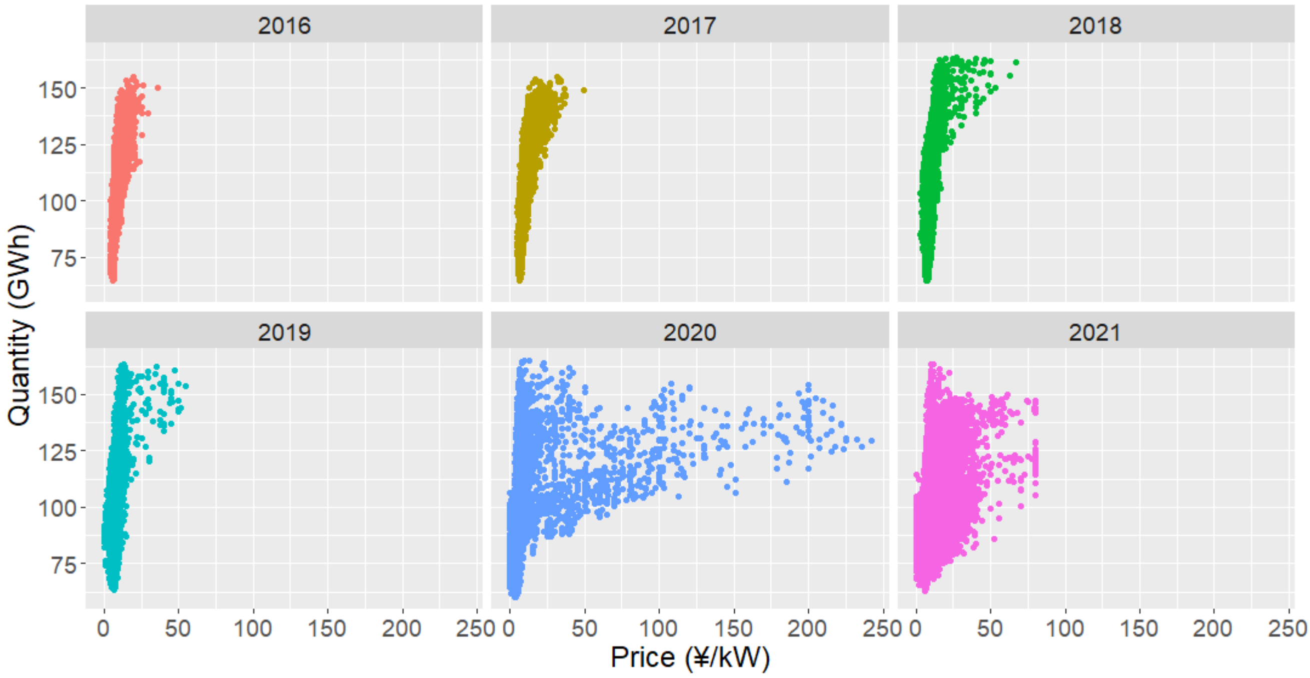

Fig. 4. Yearly Scatter Plot of Demand Quantities Versus Wholesale Market Price.

Table 2. Results of the two-stage least square regression estimation

	Estimate	Std. Error	t-value	Pr(>|t|)	
(Intercept)	4.31E-02	5.83E-03	7.395	1.43E-13	***
PRICE	1.39E-02	2.69E-04	51.517	< 2e-16	***
SUPPLY	9.98E-01	7.47E-05	13363.34	< 2e-16	***
Residual standard error:	0.2066 on 52581 degrees of freedom				
Multiple R-Squared:	0.9999	Adjusted R-squared:		0.9999	
Wald test:	2.018e+08 on 2 and 52581 DF	p-value:		< 2.2e-16	
Signif. Codes:	0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1				

Table 3. Diagnostic Tests Table

	df1	df2	statistic	p-value	
Weak instruments	6	52575	489.1	<2e-16	***
Wu-Hausman	1	52580	4218.9	<2e-16	***
Sargan	6	NA	8159.4	<2e-16	***

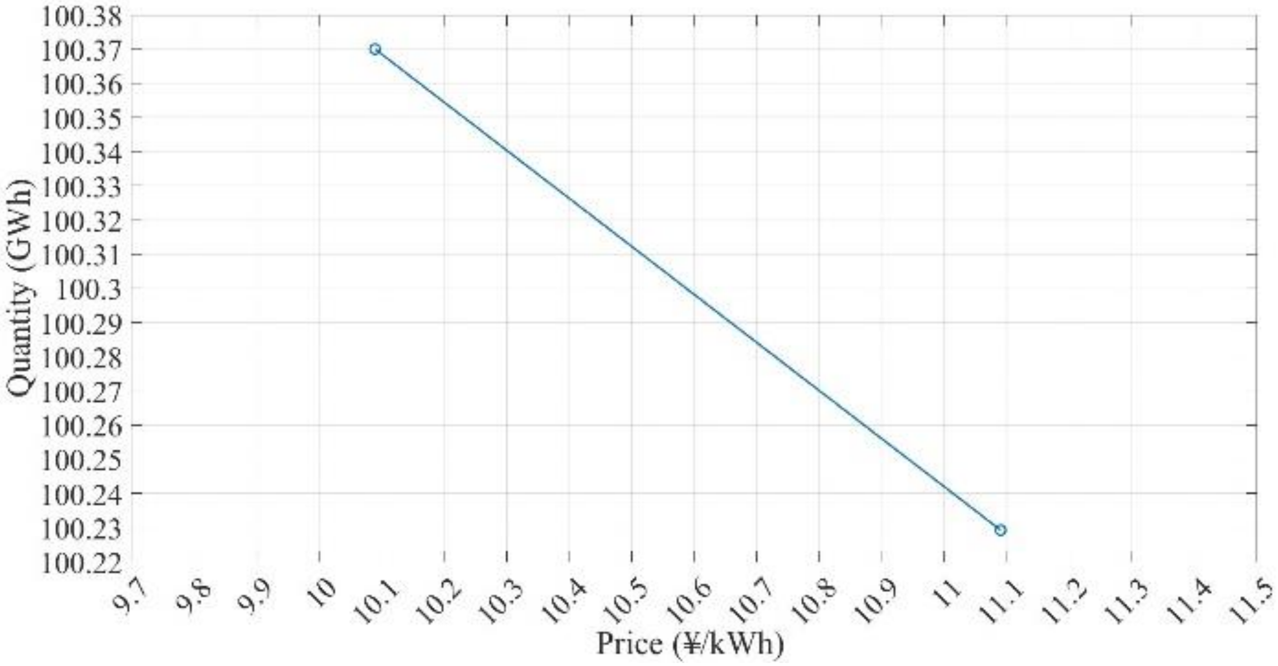

Fig. 5. The estimated demand elasticity

wholesale market price by one ¥/kWh will affect the national demand quantity by 0.14% drop, and vice versa. Estimating the demand elasticity is the fundamental step in designing efficient demand response programs, which includes sophisticated mathematical optimization from the perspectives of consumer satisfaction, dynamic elasticities, supplier strategies, and energy authority policies.

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