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Solar Surge and Retail Price Shifts: Heterogenous Redistributional Effects in Japan's Electric Bills

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Abstract:

This study examines the impact of solar energy's daily intermittency on electricity pricing, specifically investigating how the "duck curve" and "peak shifting" phenomena affect different consumer groups. Notably, commercial and industrial users exhibit higher demand around midday, while residential users' demand peaks during morning and evening hours. This disparity prompts a key question: do peak shifting and redistribution effects vary across consumer groups due to their distinct electricity consumption patterns? Our analysis focuses on Japan's power system amid significant solar energy integration, particularly the effects on residential and commercial-industrial sectors, as solar capacity expanded from 42 GW in 2016 to 83 GW in 2022. Using monthly power consumption data, we uncover that increased solar penetration results in higher electricity prices for residential consumers and reduced costs for commercial-industrial users. A central finding is the mediating role of pumped hydro storage (PHS) stations in stabilizing prices during peak and off-peak periods by managing energy demand variability, thereby mitigating economic impacts across consumer groups. The study also sheds light on the issue of cross-class subsidization, where some groups bear disproportionately higher electricity costs due to renewable energy integration. This underscores the necessity for carefully crafted policy interventions to maintain market fairness and sustainability.

Keywords: Solar Penetration, Peak Price Shifting, Cross-group Subsidization, Consumer Electricity Bills, Pumped Hydro Storage

1 Introduction

In recent years, the escalating issue of global climate change has intensified the focus on renewable energy, now playing an increasingly vital role in global energy consumption(Chu & Majumdar, 2012; Creutzig et al., 2017; Kuriyama, Liu, Naito, Tsukui, & Tanaka, 2023). Japan has witnessed a significant transformation in its energy sector. By 2022, Japan's solar energy installation capacity soared to 83 GW, surpassing natural gas units and emerging as the most extensively installed power generation technology%[1]. As per the Ministry of Economy, Trade and Industry(METI), solar power accounted for 8.3% of Japan's energy market share in 2022, with wind energy constituting 0.9(Agency for Natural Resource and Energy of Japan, 2023).

However, the variability in renewable energy output has profound implications for the electricity market's supply-demand balance. In some instances in 2022, variable renewable energy output constituted up to 69% of Japan's total electricity consumption nationwide. A notable instance occurred on May 4th, 2022, at 11 a.m., when solar power generation in the Kyushu region exceeded total power demand by 104.9%[2].

Existing literature has advanced our understanding of renewable energy's impact on wholesale electricity prices(Joskow, 2019; Maniatis & Milonas, 2022; Sakaguchi & Fujii, 2021; Tanaka, Matsumoto, Keeley, & Managi, 2022), yet the intricacies of the duck curve and peak shifting warrant further exploration(Cludius, Forrest, & MacGill, 2014). These phenomena, emerging from solar energy's intermittency, lead to pronounced electricity price fluctuations, particularly during peak demand hours. The duck curve, characterized by a midday drop in net electricity demand due to high solar output, and a subsequent evening surge as solar generation decreases, poses significant grid management challenges. Meanwhile, peak shifting reflects the volatility in electricity prices, impacting economic efficiency and disproportionately affecting certain consumer groups like residential users and small businesses. A deeper analysis is needed to assess the economic and social implications of these phenomena, particularly on varying consumer groups. Understanding their impact on energy behaviors and affordability is crucial for developing equitable and sustainable energy policies in a renewable-centric energy landscape.

In our study, we utilize a unique dataset of Japan's monthly power consumption to examine the impact of solar energy penetration on retail electricity prices for both commercial-industrial (high-voltage contracts) and residential (low-voltage contracts) users. Employing a baseline regression model, we analyze how solar energy's share, alongside other factors like wholesale electricity prices and total consumption, affects

[1] Institute for Sustainable Energy Policies (2022). 2022 *Share of Electricity from Renewable Energy Sources in Japan (Preliminary)*. Accessed November 11, 2023. https://www.isep.or.jp/en/1436/.

[2] Calculated based on data published by the Organization for Cross-regional Coordination of Transmission Operators (OCCTO) and Kyushu Electric Power Company.

electricity pricing. Our approach includes a mediation effect model to explore the "peak shifting" phenomenon, considering both off-peak (11 am, 12 pm, 1 pm) and peak periods (5 pm, 6 pm, 7 pm).

We delve into the phenomena of peak shifting and its implications for electricity pricing in Japan's solar-integrated power market. Our findings reveal a distinct impact of solar penetration on electricity prices for different consumer groups. For residential users, a 10% solar penetration rate corresponds to an increase of approximately 0.459 JPY/kWh in retail electricity prices. In contrast, commercial-industrial users experience a reduction in electricity costs by about 0.397 JPY/kWh with the same rate of solar integration. This divergence is further illuminated by the mediation effect of peak and off-peak electricity prices. The peak prices significantly mediate the increase in residential electricity costs, while off-peak prices play a similar role for commercial-industrial prices, indicating a heterogeneous response to solar penetration in peak and off-peak periods.

We also focus on the mediating role of pumped hydro storage (PHS) in moderating these effects, crucial for managing the variability of solar energy and ensuring grid stability. Our results highlight the impact of PHS's charging and discharging activities on retail electricity prices. For commercial-industrial users, the charging activities of PHS stations significantly reduce retail prices, mitigating the increase caused by solar penetration. In contrast, the discharging activities have a limited influence on residential prices, with solar penetration remaining the primary factor driving up costs. Overall, the integration of PHS is shown to be instrumental in stabilizing electricity prices, reflecting its critical function in a solar-dominated energy landscape.

The findings of our study provide a new perspective on the integration of renewable energy. Previous research has predominantly focused on the wholesale electricity market from the generation perspective. However, retail prices comprehensively consider the cumulative impact of renewable energy integration across generation, transmission, distribution, and sale. In essence, this study sheds light on the nuanced ways in which renewable energy integration, particularly solar energy, affects different consumer segments in Japan’s electricity market. It highlights both the challenges and opportunities that arise from this energy transition, offering vital insights for policymakers and stakeholders in the energy sector.

The structure of this thesis is as follows: Chapter 2 presents a concise background and literature review. Chapter 3 describes the data and empirical methods used. Chapter 4 reports the baseline regression results, while Chapter 5 delves into the mechanism of impact through a mediation effect model. Chapter 6 examines the mediating role of pumped hydro storage. The final chapter offers conclusions and policy recommendations.

2 Background and Literature Review

The energy landscape is undergoing a transformative shift towards sustainability, reflecting global efforts to integrate renewable sources into the power grid(Gielen et al., 2019; Jones, 2017). A substantial body of literature has focused on the implications of this transition, particularly regarding electricity market dynamics and pricing structures(Amountzias, Dagdeviren, & Patokos, 2017; Mahler, Girard, & Kariniotakis, 2022). The 'Duck Curve' and 'peak shifting' have emerged as significant phenomena in the discourse, representing the challenges and opportunities inherent in the evolving energy paradigm(Hou et al., 2019; Kalair et al., 2021; Torabi, Gomes, & Morgado-Dias, 2018).

2.1 Duck Curve and Peak shifting in the Japanese Power System

In Japan solar power's integration has notably reshaped electricity demand patterns, with photovoltaic installations now eclipsing liquefied natural gas to become the country's largest single generation technology[3]. This shift has brought the 'Duck Curve' phenomenon to the fore, graphically representing the interplay between solar production and the rest of the power demand throughout the day. The trend underscores a significant transition in energy consumption habits and market dynamics, as Japan's energy mix has seen a decisive move towards solar in the last decade (Hou et al., 2019; Pitra & Musti, 2021). Accompanying this shift is the 'peak shifting' dynamic, evident through price spikes during morning and evening peak periods, signaling an increasing imperative for grid flexibility and advanced energy management strategies.

As depicted in Figure 2, the 'Duck Curve' phenomenon in the Kyushu region from 2016 to 2022 is clearly presented. The variation in residual electricity demand across the years is differentiated by the colors of the lines. The sun icons indicate the impact of solar power generation during the daytime, and the duck-shaped contour within the graph embodies the so-called 'Duck Curve.' It is evident from Figure 1 that, as the years progress, the midday residual electricity demand decreases due to the increase in solar power generation, with a rapid rise observed towards the evening. This trend is particularly pronounced in 2022, suggesting a significant surge in solar power output. With the reduction of solar power generation at night, other sources of electricity are required to meet the shortfall, leading to this pattern of demand fluctuation. This graph provides us with a visual representation of the impact of the growth in solar power generation on the balance of electricity supply and demand, underscoring the vital role of renewable sources in the power system.

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[3] According to the *Renewable Capacity Statistics 2023* published by the International Renewable Energy Agency, as of March 2023, Japan's solar energy installation capacity reached 79 gigawatts (GW). Concurrently, data from the Agency for Natural Resources and Energy's Monthly Electricity Survey Statistics indicate that the installed capacity for liquefied natural gas (LNG) stands at 77.34 GW. Consequently, solar energy has surpassed natural gas generation to become the largest electricity generation technology in Japan in terms of installed capacity.

Figure 1 illustrates the trend of electricity prices (in yen per kilowatt-hour) across various times of the day from 2016 to 2022. The lines of varying colors distinguish between the years. Notably, there has been a significant rise in electricity prices during the evening hours in recent years, especially in 2021 and 2022. In 2022, the price peaked at nearly 30 yen per kilowatt-hour in the evening. In contrast, from 2016 to 2020, the prices during this time were relatively stable with minimal fluctuations. Additionally, there is a downward trend in prices around noon, which correlates with the high output of solar power generation during the day, potentially leading to an increase in electricity supply and a consequent drop in prices. Overall, the chart presents a clear depiction of how electricity prices vary over time and with the output of renewable energy, revealing the impact of the supply-demand relationship in the power market on pricing.

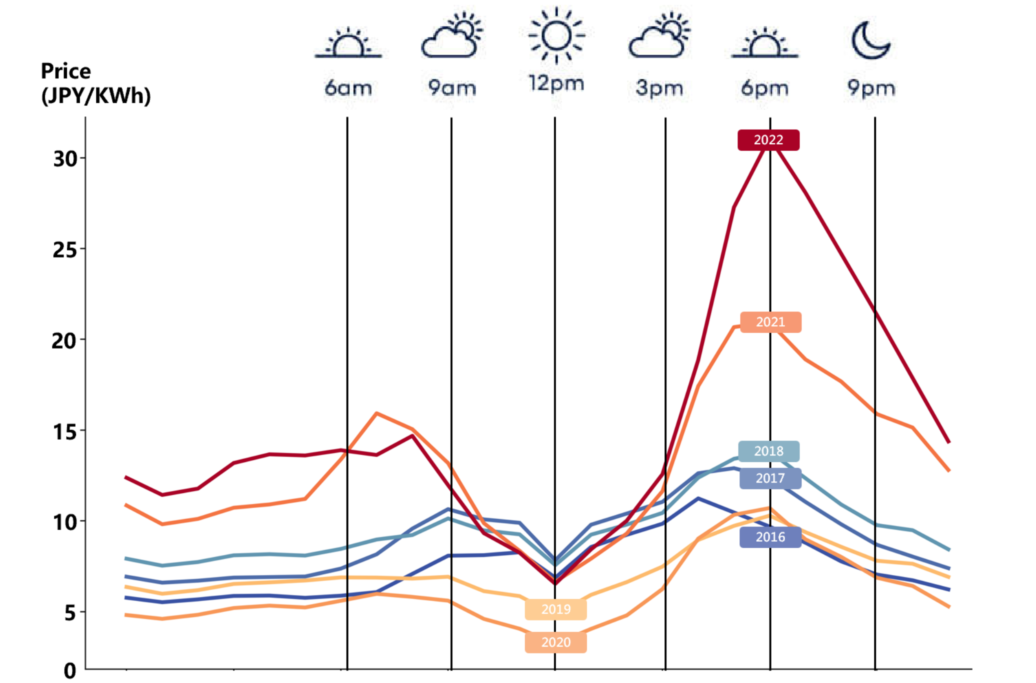

Figure 1 Peak Shifting Phenomenon in Kyushu Region from 2016 to 2022

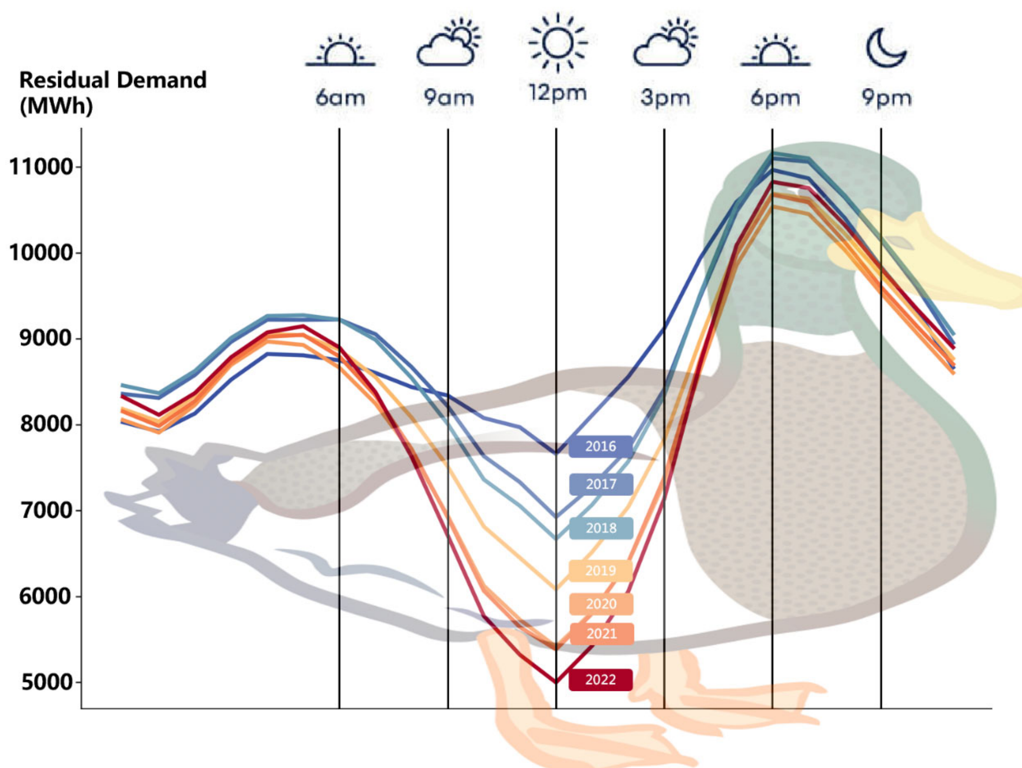

Figure 2 The Duck Curve Phenomenon from 2016 to 2022 in Kyushu

2.2 Literature Review and Research Question

The integration of renewable energy into electricity markets has prompted a significant scholarly interest, particularly concerning its implications on pricing dynamics. While the Merit-order effect (MOE) provides an established framework for understanding how renewable energy can influence wholesale prices (Oosthuizen, Inglesi-Lotz, & Thopil, 2022; Sakaguchi & Fujii, 2021), recent literature has called attention to the nuanced patterns of demand and supply that emerge from this integration(Cludius et al., 2014). The "duck curve" and "peak shifting" phenomena are outcomes of this complex interplay, reflecting the operational challenges and economic impacts that renewables, particularly solar energy, bring to the power grid.

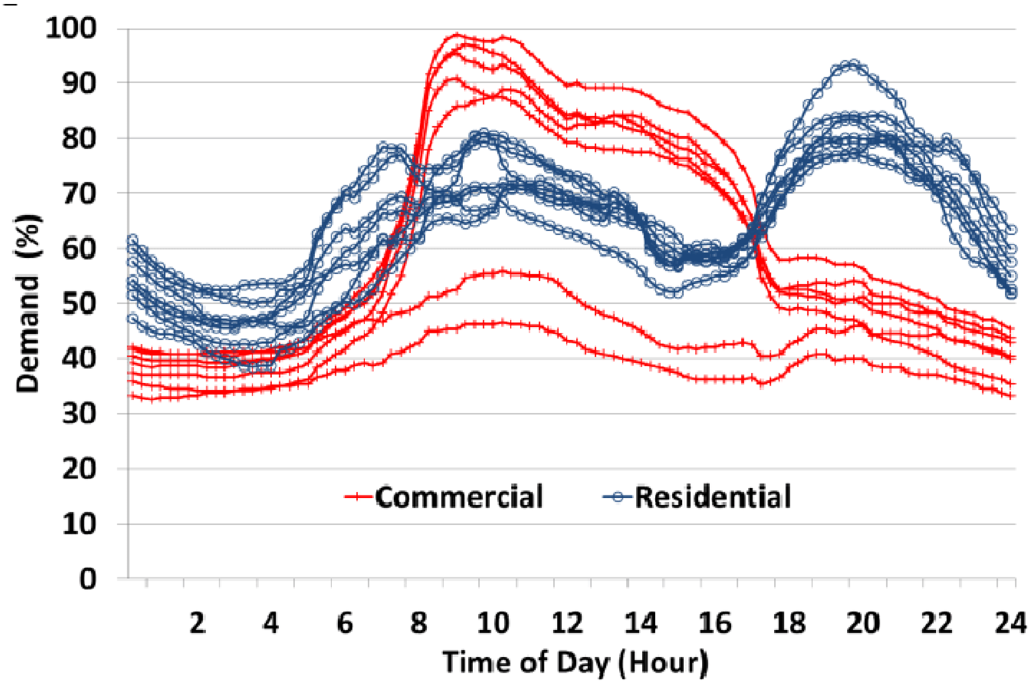

Figure 3　Daily load/Demand Profile of Commercial and Residential Users

Source: Joshi and Lakum (2014)

This study builds upon these insights and seeks to address a gap in the current research landscape. It focuses on the repercussions of solar energy's diurnal intermittency, as captured by the "duck curve" and subsequent "peak shifting" phenomena, on different consumer groups within Japan's energy market. Joshi and Lakum (2014) work on daily load and demand profiles of commercial and residential users provides a foundational reference for understanding these groups' consumption behaviors and their potential vulnerability to energy price volatility(see in Figure 3). , Johnson et al. (2017) employ an optimal power flow model to simulate various scenarios within a particular US electric grid. One of their key findings indicates that the diurnal variability of solar energy, coupled with the distinct daily electricity consumption patterns of residential and commercial-industrial users, results in divergent impacts on the electricity bills of these consumer groups due to solar integration. Specifically, their study suggests that residential electricity bills are likely to increase while those of commercial and industrial users may decrease. This outcome is attributed to the peak shifting caused by solar energy's intermittency, which leads to a reallocation of costs between different user categories. The study underscores the complexities of integrating solar PV into the grid and the consequent need for nuanced policy approaches to address the potential for cross-subsidization and ensure equitable cost distribution among consumer groups.

Hence, the core research question emerges: In the context of Japan's evolving energy sector, how does solar integration, manifesting through the "duck curve" and "peak shifting," differentially affect electricity pricing for commercial versus residential users? This question invites a comprehensive analysis of the economic ramifications of solar energy penetration, aiming to untangle the shifts in electricity costs across diverse user groups. Such an inquiry is essential for informing policy strategies that balance the advancement of renewable energy with the safeguarding of equitable and sustainable market conditions.

3 Datasets and Empirical Strategies

3.1 Datasets

Our analysis utilizes data from the "Monthly Electricity Transaction Status" report released by the Japan Electric Power and Gas Trading Surveillance Commission. This report offers a wealth of information on monthly electricity consumption for residential and commercial institutions, including average monthly electricity usage per household, pricing, and more. As evident in Table 1, the average monthly electricity consumption for residential use is approximately 225 kWh, while for commercial and industrial users, it stands at 28,174 kWh.

The dependent variables in our study are the average monthly electricity prices for the residential sector and commercial and industrial sectors. These are calculated by dividing the total amount billed under the low-voltage lighting contracts and high-voltage contracts by the total electricity consumption under these contracts, respectively. As our main explanatory variable, we use the proportion of solar energy, primarily due to the significant regional differences in demand. The dimensionless ratio of solar energy, as opposed to the absolute solar output, better reflects the impact of changes in the share of solar energy.

To ensure the robustness and accuracy of our model's results, we incorporated a series of control variables in addition to the proportion of solar power generation to mitigate any bias from omitted variables.

- Wholesale Electricity Prices:

Wholesale electricity price serves as a key control variable in our model, reflecting the marginal cost of power supply. Increases in price may be attributed to rises in raw material costs, maintenance expenses of the power grid, or other production-related cost factors. By controlling for this variable, we aim to ensure that the results are not influenced by these cost effects, thus isolating the net effect of the proportion of solar power generation on electricity prices.

- Monthly Consumption Amount per Contract Type:

The consumption amount reflects the overall demand for electricity. The scale of electricity consumption may vary across different contracts or regions, which in turn, can affect electricity prices. For example, large-scale consumption due to economies of scale could result in a lower price per unit of electricity. Introducing this control variable allows our model to distinguish between the supply effect of solar power and the overall demand or scale effects.

With the introduction of these control variables, we intend for our model to more accurately reveal the relationship between solar power generation and the monthly average electricity prices for residential and commercial-industrial sectors, eliminating the influence of other potential confounders.

Table 1 Differences in Electricity Contracts and Consumption Behaviors among User Types

Contract Type	Voltage	Contract Description	User Type	Electricity Sales (MWh) (Oct 2022)	Number of Contracts (Oct 2022)	Average Monthly Electricity Consumption per Contract(kWh)	Consumption Share (Oct 2022)
High-Voltage	6,600 V	For corporate electricity needs: Contracts ranging from 50 to 2000 kW	Primarily small-scale businesses, including convenience stores, restaurants, kindergartens, nurseries, hospitals, offices, and small factories.	22,579,682	801,428	28,174.31	36.4%
Low-Voltage (Lighting)	100V and 200V	Single-phase with contract power less than 50 kW	Primarily residential users and small-scale commercial establishments.	18,592,222	82,665,977	224.91	30.0%

Table 2 Descriptive Statistics

Variables	*Unit*	*count*	*mean*	*sd*	*min*	*max*
Residential Price	JPY/kWh	711	18.962	2.455	13.444	28.380
I&C Price	JPY/kWh	711	12.948	2.109	8.467	23.578
Wholesales Price	JPY/kWh	711	11.686	8.321	3.520	71.848
Peak Price	JPY/kWh	711	15.728	12.921	5.594	111.389
Off-Peak Price	JPY/kWh	711	9.136	5.189	1.397	43.022
Solar Ratio	%	711	0.081	0.044	0.007	0.225
Residential Consumption	GWh	711	2490	2160	481	11500
I&C Consumption	GWh	711	2760	2150	693	9830
Monthly Salary	GPY	711	345	272	182	2980
Electricity Import	GWh	711	530	800	0.000	4030
Pumped Hydro Charge	GWh	711	103	134	0.000	966
Pumped Hydro Discharge	GWh	711	54	101	0.000	679

3.2 The Baseline Model

To examine the influence of solar energy on retail electricity prices, we employ the following regression equation:

$$P_{it}^{Retail} = \beta_0 + \beta_1 SolarRatio_{it} + \beta_2 Q_{it}^{contract} + \beta_3 P_{it}^{Wholesales} + \lambda_i + \eta_t + \varepsilon_{it}$$

where:

P_{it}^{Retail} represents the retail price for electricity for residential or commercial and industrial users in region i during month t. $SolarRatio_{it}$ is the proportion of solar energy generation to total electricity demand in region i during month t. $Q_{it}^{contract}$ is the total electricity consumption for residential or commercial and industrial contracts in region i during month t. $P_{it}^{Wholesales}$ is the wholesale electricity price in region i during month t. λ_i and $\eta_t$represent the regional and time fixed effects, respectively. ε_{it} is the error term.

Descriptive statistics presented in

Table 2 reveal that the average retail price for electricity in the residential sector is 18 JPY/kWh, which is higher than that for the commercial and industrial sector, at 12 JPY/kWh. The average wholesale electricity price is 11 JPY/kWh, yet with a standard deviation of 8 JPY/kWh, indicating much greater volatility compared to retail prices. The solar energy proportion has an average value of 8.1%.

3.3 The Mediation Model

To delve into the underlying factors of the results, we conducted an in-depth exploration of the "peak shifting" phenomenon. In line with the characteristics of the Duck Curve, we consider the electricity prices at 11 am, 12 pm, and 1 pm as indicative of the off-peak period, while the prices at 5 pm, 6 pm, and 7 pm are considered representative of the peak period. We propose the following hypotheses:

H1: The substantial integration of solar energy into the grid causes an increase in peak period electricity prices, thereby raising the cost of electricity for households.

H2: The large-scale adoption of solar energy results in an increase in non-peak electricity prices, leading to a reduction in electricity costs for commercial and industrial usage.

This scenario can be viewed as a typical mediation effect model. To understand the observed phenomena, we utilize a mediation effect model to explore the relationship between solar energy integration into the grid and electricity prices. Mediation effect models are used to reveal the inner mechanisms of the relationship between an independent variable and a dependent variable, namely, how the mediator variable transmits or moderates this relationship. In the context of this study, we hypothesize that the integration of solar energy into the grid (independent variable) may affect electricity prices during specific periods (mediator variable), which in turn impacts the electricity costs for residential and commercial-industrial usage (dependent variable).

To test these hypotheses, data collection and statistical testing via regression analysis or structural equation modeling are required. Initially, we construct a model that includes the independent variable, mediator variable, and dependent variable as follows:

$$\begin{cases} P_{it}^{Retail} = \beta_0 + \beta_1 SolarRatio_{it} + \beta_2 Q_{it}^{contract} + \beta_3 P_{it}^{Wholesales} + \lambda_i + \eta_t + \varepsilon_{it} & (Step\ 1) \\ P_{it}^{Peak} = \gamma_0 + \gamma_1 SolarRatio_{it} + \gamma_2 Q_{it}^{contract} + \gamma_3 P_{it}^{Wholesales} + \lambda_i + \eta_t + \varepsilon_{it} & (Step\ 2) \\ P_{it}^{Retail} = \beta_0 + \beta_1 SolarRatio_{it} + \theta P_{it}^{Peak} + \beta_2 Q_{it}^{contract} + \beta_3 P_{it}^{Wholesales} + \lambda_i + \eta_t + \varepsilon_{it} & (Step\ 3) \end{cases}$$

Step 1: Testing for Total Effects

The initial equation investigates the direct impact of the solar penetration ratio, $SolarRatio_{it}$, on the retail electricity prices, P_{it}^{Retail}. Here, our focus is on the coefficient β_1 which indicates how retail electricity prices will change for each unit change in the solar penetration ratio.

Step 2: Testing Mediation Pathways

The subsequent equation examines the effect of the solar penetration ratio, $SolarRatio_{it}$on peak electricity prices, P_{it}^{Peak}. In this case, we are concerned with the coefficient γ_1, representing the impact of the solar penetration ratio on peak electricity prices.

Step 3: Determining and Testing for Mediation Effects

The coefficient in this equation indicates the change in retail electricity prices for each unit change in peak electricity prices. If it is significantly positive, it confirms that peak electricity prices indeed have a significant impact on retail electricity prices. Should the coefficient β_1 become insignificant upon the introduction of the mediator variable, it would suggest that peak electricity prices, P_{it}^{Peak}, fully mediate the relationship between the solar penetration ratio, $SolarRatio_{it}$, and retail electricity prices, P_{it}^{Retail} constituting a 'full mediation model'. Conversely, if β_1 remains significant but decreases in value, it would indicate a 'partial mediation model', where the mediation effect is partial.

In summary, by combining Equation (1), Equation (2), and Equation (3), we can determine whether there is a mediation effect in the relationship between the solar penetration ratio and retail electricity prices and if so, whether this mediation effect is complete or partial.

4 The baseline results

Our initial exploration focused on the potential impacts of solar power generation's share on retail electricity prices across various contract types. The detailed regression results are presented in Table 3 and Table 4. The results reveal that the penetration of solar power generation has exerted varying effects on the retail electricity prices of different contract types.

As shown in Table 3, for residential users, solar energy integration correlates with a notable increase in retail electricity prices. Specifically, the retail electricity prices for residential users have experienced significant upward pressure. Taking the 2022 data as an example, with a solar penetration rate of 10% across regional power grids, the residential retail electricity price is expected to increase by approximately 0.459 JPY/kWh. Considering the annual average electricity consumption for households in 2022, which is 3273 kWh, the liberalization of the power retail market could lead to an additional annual expenditure of about 1502 JPY for household users.

Table 3 The Impact of Solar Penetration on Residential Electricity Retail Prices

	(1) Residential Price	(2) Residential Price	(3) Residential Price	(4) Residential Price	(5) Residential Price
Solar Penetration Rate	3.734*	3.734*	5.615***	4.144**	4.347**
	(2.094)	(2.094)	(2.028)	(2.025)	(2.036)
Month Count		0.055***	0.031***	0.027***	0.027***
		(0.004)	(0.005)	(0.005)	(0.005)
Regional Wholesale Price			0.124***	0.123***	0.124***
			(0.017)	(0.017)	(0.017)
Electricity Consumption(log)				-1.756***	-1.695***
				(0.395)	(0.400)
Electricity Import(log)					-0.013
					(0.014)
Constant	20.187***	20.132***	19.127***	44.586***	43.776***
	(0.257)	(0.259)	(0.284)	(5.731)	(5.793)
Month Dummy	Y	Y	Y	Y	Y
Region Dummy	Y	Y	Y	Y	Y
Samples	711	711	711	711	711
Groups	9	9	9	9	9
Adj R2	0.850	0.850	0.862	0.866	0.866
F	52.032	52.032	56.361	57.590	56.892
rho	0.879	0.879	0.873	0.933	0.933

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Conversely, for commercial and industrial sectors, particularly medium to large-scale enterprises, the impact is inversely proportional. The regression results are detailed in Table 4. From the analysis, we observe that, contrary to residential users, an increase in solar power generation has a significant negative effect on the retail electricity prices for medium to large-scale commercial and industrial users. Specifically, a 10% increase in solar penetration is expected to decrease the average electricity prices paid by these users by approximately 0.397 JPY/kWh. This outcome is likely due to the alignment of high daytime electricity demand from these users with the high supply period of solar energy, allowing them to benefit more substantially. Furthermore, due to their large-scale electricity consumption, the relatively lower electricity prices can result in significant economic benefits for these users.

Previous studies have suggested that the variability of renewable energy sources could contribute to an increase in the energy burden (Brown, Soni, Lapsa, Southworth, & Cox, 2020). From our investigation, the impact appears to be significant but minimal. Our findings are largely in line with those of Johnson et al. (2017), indicating that for residential households, with an average electricity price of 18.92 JPY/kWh, the integration of solar energy has led to a 2.43% increase in electricity costs; whereas for commercial and industrial users, with an average electricity price of 12.94 JPY/kWh, solar integration has resulted in a 3.07% decrease in electricity costs.

Table 4 baseline The Impact of Solar Penetration on Commercial-Industrial Electricity Retail Prices

	(1) I&C Price	(2) I&C Price	(3) I&C Price	(4) I&C Price	(5) I&C Price
Solar Penetration Rate	-4.238**	-4.238**	-1.637	-4.257**	-4.233**
	(2.017)	(2.017)	(1.862)	(1.771)	(1.781)
Month Count		0.056***	0.022***	0.023***	0.023***
		(0.004)	(0.005)	(0.005)	(0.005)
Regional Wholesale Price			0.172***	0.163***	0.163***
			(0.016)	(0.015)	(0.015)
Electricity Demand(log)				-4.661***	-4.652***
				(0.507)	(0.511)
Electricity Import(log)					-0.002
					(0.012)
Constant	16.612***	16.556***	15.168***	83.022***	82.903***
	(0.247)	(0.249)	(0.261)	(7.378)	(7.431)
Region Dummy	Y	Y	Y	Y	Y
Month dummy	N	Y	Y	Y	Y
Samples	711	711	711	711	711
Groups	9	9	9	9	9
Adj R2	0.865	0.865	0.887	0.901	0.900
F	58.918	58.918	70.884	80.473	79.367
rho	0.764	0.764	0.741	0.976	0.976

Standard errors in parentheses
* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

The estimated coefficients for the other control variables are consistent with our expectations. Specifically, in the regional wholesale electricity market, there is a notable positive correlation with retail electricity prices. For instance, a 1 JPY/kWh increase in wholesale prices typically leads to an approximate increase of 0.13 JPY/kWh in residential electricity prices and about 0.16 JPY/kWh for commercial and industrial electricity prices. Additionally, there is a clear scale effect present in the retail electricity market. For example, with each 1% increase in residential electricity volume, the price is observed to decrease by 1.68 JPY/kWh; for commercial and industrial consumption, each 1% increase correlates with a decrease of 4.591 JPY/kWh in the price.

5 Mechanism: The Impact of Peak Shifting

In the previous chapter, we detailed the significant impacts of solar penetration on retail electricity prices across different consumer groups. The introduction of solar energy has led to the pronounced phenomenon of "peak shifting" in Japan. This trend indicates a potential shift in the traditional patterns of peak and off-peak electricity pricing, especially during periods with substantial solar energy integration into the grid. In this chapter, we delve into whether solar penetration has a heterogeneous impact on wholesale electricity prices during peak and off-peak periods, and how this "peak shifting" is reshaping the pricing structure of the electricity market.

5.1 Heterogeneous Response of Peak and Off-Peak Electricity Prices to Solar Penetration

As indicated in Column (1) in Table 5, the impact of solar penetration on peak electricity prices initially appears to be insignificant. However, when month dummy variables and other control variables are incorporated, solar penetration exhibits a significant positive effect on peak period prices. Conversely, solar penetration has a consistent negative impact on off-peak electricity prices, as confirmed in Column (2) and Column (4). Collectively, these findings suggest that solar penetration indeed has a heterogeneous effect on electricity prices during peak and off-peak periods, likely due to the distinctive supply characteristics of solar energy and the demand patterns of the electricity market.

Table 5 The Impact of Solar Penetration on Wholesale Electricity Prices During Peak and Off-Peak Periods

	(1) Peak Price	(2) Peak Price	(3) Off-Peak Price	(4) Off-Peak Price
Solar Penetration Rate	-3.927	12.408***	-30.166***	-12.970***
	(6.351)	(3.958)	(6.068)	(3.062)
Month Count		0.083***		-0.146***
		(0.010)		(0.008)
Wholesale Price		1.071***		1.116***
		(0.033)		(0.026)
Electricity Import(log)		0.024		-0.034
		(0.777)		(0.021)
Constant	9.015***	-0.013	8.893***	0.048
	(0.779)	(0.027)	(0.744)	(0.445)
Region Dummy	Y	-0.170	Y	Y
Month dummy	N	(11.261)	Y	Y
Samples	711	Y	711	711
Groups	9	Y	9	9
Adj R2	0.974	711	0.845	0.962
F	341.789	9	50.250	220.089
rho	0.286	0.991	0.286	0.089

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

5.2 Testing Results of the Mediation Effects of Peak and Off-Peak Prices

In light of the impact of solar energy integration on electricity pricing, we further investigated how this effect is mediated to different electricity consumers through peak and off-peak prices. Specifically, we examined scenarios of rising peak prices and falling off-peak prices, testing how these variations serve as mediating factors affecting the retail prices for residential and commercial-industrial users.

Table 6 presents the effects of solar penetration on peak prices and residential retail prices. Column (1) indicates that solar penetration significantly increases retail prices for residential users. Column (2) reveals that solar penetration also significantly raises peak prices. Moreover, in Model (3), when controlling for peak prices, the effect of solar penetration becomes insignificant, while the mediating effect of peak prices becomes significant. This suggests that the increase in peak prices is an important mediating factor in the rise of residential retail prices due to solar penetration.

Table 6 Testing the Mediating Effect of Peak Prices on Residential Electricity Prices

	(1)	(2)	(3)
	Residential Price	Peak Price	Residential Price
Solar Penetration Rate	4.587**	12.235***	2.585
	(1.996)	(3.879)	(2.072)
Peak Price			0.057***
			(0.013)
Month Count	0.031***	0.084***	0.035***
	(0.005)	(0.010)	(0.006)
Electricity Import(log)	-0.019		-0.007
	(0.014)		(0.014)
Electricity Demand(log)	-1.687***		-1.753***
	(0.392)		(0.411)
Salary(log)	-0.461***		
	(0.089)		
Regional Wholesale Price	0.123***	1.070***	
	(0.017)	(0.033)	
Constant	49.425***	0.091	45.086***
	(5.780)	(0.543)	(5.944)
Region Dummy	Y	Y	Y
Month dummy	Y	Y	Y
Samples	711	711	711
Groups	9	9	9
Adj R2	0.871	0.991	0.858
F	58.877	933.327	53.576
rho	0.938	0.113	0.933

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

In Table 7, we examined the effects of solar penetration on off-peak prices and commercial-industrial retail prices. Column (1) demonstrates that solar penetration significantly reduces the retail prices for commercial-industrial users. Furthermore, Column (2) shows that solar penetration significantly lowers off-peak prices. In Column (3), when controlling off-peak prices, the effect of solar penetration on commercial-industrial retail prices becomes insignificant, whereas the mediating effect of off-peak prices is significant. This indicates that the decline in off-peak prices is a key mediating factor in the reduction of commercial-industrial retail prices attributable to solar penetration.

Table 7 Testing the Mediating Effect of Off-Peak Prices on Commercial-Industrial Electricity Prices

	(1)	(2)	(3)
	Step 1 I&C Price	Step 2 Off-Peak Price	Step 3 I&C Price
Solar Penetration Rate	-3.974**	-12.970***	-2.658
	(1.739)	(3.062)	(1.969)
Off-Peak Price			0.100***
			(0.013)
Month Count	0.026***	-0.146***	0.045***
	(0.005)	(0.008)	(0.004)
Electricity Import(log)	-0.007	-0.034	0.002
	(0.012)	(0.021)	(0.013)
Electricity Demand(log)	-4.591***		-1.729***
	(0.499)		(0.383)
Regional Wholesale Price	0.162***	1.116***	
	(0.014)	(0.026)	
Constant	87.473***	0.048	40.709***
	(7.298)	(0.445)	(5.541)
Region Dummy	Y	Y	Y
Month dummy	Y	Y	Y
Samples	711	711	711
Groups	9	9	9
Adj R2	0.905	0.962	0.881
F	82.693	220.089	65.037
rho	0.977	0.089	0.882

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Overall, these results validate our hypothesis that the substantial integration of solar energy, leading to changes in peak and off-peak electricity prices, acts as a mediating factor influencing the retail electricity prices of different types of users.

6 Mechanism: The Value of Electricity Storge

With the increase in solar energy integration, the role of pumped hydroelectric storage (PHS) stations as energy storage facilities has become increasingly critical (Kosowatz, 2018). These stations contribute to the regulation of electricity supply and demand by charging during off-peak periods and discharging during peak periods, thus influencing retail electricity prices (Newbery, 2018; Rana et al., 2023; Schmalensee, 2022). As of 2022, Japan has an installed capacity of 27 gigawatts (GW) in PHS systems, serving as a vital component of the national grid's peak load management, which is approximately 102 GW. With solar power generating peak outputs around 50 GW, PHS has affirmed its role as Japan’s principal regulator in the electricity supply system. This synergy underscores the strategic importance of PHS in mitigating the variability of renewable sources and ensuring grid stability, marking it as an essential element of Japan's energy strategy. To gain a deeper understanding of this mechanism, we employed a mediation effect model to examine the impact of the charging and discharging activities of PHS stations on the retail electricity prices for residential and commercial-industrial users.

6.1 The Mediating Effect of Pumped Hydro Storage Charging Activities on Commercial-Industrial Electricity Prices

Table 8 delineates the influence of solar penetration on commercial-industrial retail electricity prices, as well as the mediating role of pumped hydro storage (PHS) charging activities. Column (1) illustrates that solar penetration significantly reduces commercial-industrial retail electricity prices. Column (2) further indicates that solar penetration significantly boosts the charging activities of PHS stations. When incorporating both solar penetration and PHS charging activities in Column (3), the charging activities of PHS stations are shown to significantly negatively impact commercial-industrial retail electricity prices, while the effect of solar penetration, though weakened, remains significant. These results suggest that with the rise of solar energy, the charging activities of PHS stations mitigate the supply pressure during peak periods, thereby exerting a dampening effect on commercial-industrial retail electricity prices. Overall, as the proportion of solar energy increases, the charging activities of PHS stations counterbalance its negative impact on electricity prices, contributing positively to the stabilization of commercial-industrial retail electricity prices.

Table 8 The Mediating Effect of Pumped Hydro Storage (PHS) Charging Activities on Commercial-Industrial Electricity Prices

	(1)	(2)	(3)
	Step 1 I&C Price	Step 2 Pumped Charge	Step 3 I&C Price
Solar Penetration Rate	-4.233**	8.184**	-3.752**
	(1.781)	(3.374)	(1.780)
Pumped Hydro Charge(log)			-0.059***
			(0.021)
Month Count	0.023***	-0.000	0.023***
	(0.005)	(0.009)	(0.005)
Electricity Import(log)	-0.002	0.053**	0.001
	(0.012)	(0.023)	(0.012)
Regional Wholesale Price	0.163***	0.044	0.166***
	(0.015)	(0.028)	(0.015)
Electricity Demand(log)	-4.652***	1.219	-4.581***
	(0.511)	(0.968)	(0.509)
Constant	82.903***	-9.112	82.369***
	(7.431)	(14.077)	(7.393)
Samples	711	711	711
Groups	9	9	9
Adj R2	0.900	0.113	0.901
R2-overall	0.175	0.477	0.174
R2-within	0.913	0.225	0.914
R2-between	0.010	0.577	0.010
F	79.367	2.200	79.357
rho	0.976	0.652	0.976

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

6.2 The Mediating Effect of Pumped Hydro Storage Charging Activities on Residential Electricity Prices

Table 9 investigates the effects of solar penetration and the discharging activities of pumped hydro storage (PHS) stations on residential retail electricity prices. Column (1) indicates that solar penetration significantly increases residential retail electricity prices. Column (2) reveals that solar penetration significantly reduces the discharging activities of PHS stations. When both solar penetration and PHS discharging activities are considered in Column (3), the impact of discharging activities on residential retail electricity prices is not significant. These results suggest that while the discharging activities of PHS stations help alleviate supply pressure during off-peak periods, their influence on residential retail electricity prices is relatively limited. The effects of solar penetration remain the primary driver behind the increase in residential retail electricity prices.

Table 9 The Mediating Effect of Pumped Hydro Storage (PHS) Discharging Activities on Residential Electricity Prices

	(1)	(2)	(3)
	Step 1 Residential Price	Step 2 Pumped Discharge	Step 3 Residential Price
Solar Penetration Rate	4.347**	-12.505**	4.388**
	(2.036)	(5.503)	(2.046)
Pumped Hydro Discharge(log)			0.003
			(0.015)
Month Count	0.027***	0.138***	0.027***
	(0.005)	(0.015)	(0.006)
Electricity Import(log)	-0.013	0.033	-0.013
	(0.014)	(0.037)	(0.014)
Regional Wholesale Price	0.124***	0.041	0.124***
	(0.017)	(0.046)	(0.017)
Electricity Demand(log)	-1.695***	-0.124	-1.694***
	(0.400)	(1.081)	(0.400)
Constant	43.776***	1.823	43.770***
	(5.793)	(15.657)	(5.798)
Samples	711	711	711
Groups	9	9	9
Adj R2	0.866	0.897	0.865
F	56.892	76.552	56.120
rho	0.933	0.391	0.933

Standard errors in parentheses

* $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$

Overall, pumped hydro storage (PHS) stations play a critical role in regulating the balance of electricity supply and demand. Particularly with the substantial integration of solar energy, PHS stations provide crucial peak-shaving capabilities through their charging and discharging activities, resulting in differential impacts on the retail electricity prices for residential and commercial-industrial users.

7 Conclusion and Policy Implication

This research, through its comprehensive analysis of solar energy penetration in Japan, underscores the intricate dynamics between renewable energy integration and electricity pricing. Our findings reveal that the increase in solar energy significantly influences retail electricity prices, demonstrating a heterogeneous impact on different consumer groups. The residential sector experiences an increase in electricity prices, while commercial-industrial users benefit from reduced costs. This divergence is accentuated by the mediating role of peak and off-peak electricity prices, reflecting the distinct consumption patterns of these user groups.

Central to our study is the role of pumped hydro storage (PHS) stations in moderating the effects of solar penetration. The charging activities of PHS stations effectively mitigate the increased electricity prices for commercial-industrial users, highlighting the critical function of energy storage in maintaining grid stability and balancing supply-demand dynamics in a renewable-centric landscape. Conversely, the discharging activities of PHS stations have a limited impact on residential prices, with solar penetration remaining the predominant factor for price increases.

Our research contributes to the broader discourse on sustainable energy transitions, emphasizing the need for balanced and equitable approaches in power system development. It underscores the importance of considering the differential impacts of renewable energy integration across consumer segments, which is crucial for developing fair and sustainable energy policies. Policymakers and stakeholders in the energy sector must recognize the nuances of renewable energy integration, particularly solar energy, and its varying effects on different consumer groups. This understanding is vital for crafting policies that ensure equitable access to energy and foster a resilient and sustainable energy system.

In conclusion, the study highlights the complexity of integrating renewable energy into existing power systems and the need for innovative solutions like pumped hydro storage and demand response to manage these challenges effectively. As the world moves towards more sustainable energy sources, it is imperative to address these nuances to ensure a transition that is both environmentally sustainable and socially equitable.

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