京都大学大学院経済学研究科
再生可能エネルギー経済学講座
ディスカッションペーパー

Higher Stakes, Lower Gains:

Analyzing the Revenue Cannibalization Effect of Renewable Energies in the Electricity Market with PyPSA-Japan2050 Model

2024 年 3 月

March 2024

Zhang Tuo

Assistant Professor,

Research Project on Renewable Energy Economics,

Graduate School of Economics, Kyoto University

Higher Stakes, Lower Gains: Analyzing the Revenue Cannibalization Effect of Renewable Energies in the Electricity Market with PyPSA-Japan2050 Model

Zhang Tuo[a]

a. Assistant Professor, Research Project on Renewable Energy Economics,

Graduate School of Economics, Kyoto University

Abstract: Previous research has highlighted the challenge of integrating renewable energies into electricity markets, particularly in maintaining market value amidst the increasing penetration. This paper builds on this foundation, exploring how renewable energies can be effectively promoted as a primary power source in Japan's electricity market post-grid parity. It delves into the trend of declining market value for renewables with increased market shares, influenced by their intermittency and non-dispatchability. With renewables reaching grid parity, the study, using the PyPSA-Japan-2050 Model, confirms the revenue cannibalization effect in Japan's solar, offshore, and onshore wind sectors, noting market value declines as penetration grows. We propose that enhanced carbon pricing policies could mitigate this decline, offering new strategies for sustainable energy development. We also consider the role of demand response mechanisms, such as electric vehicle batteries, in enhancing market value and stabilizing energy prices.

Keywords: Renewable Energy Integration, Market Value Dynamics, PyPSA-Japan-2050 Model, Carbon Pricing Policy, Demand Response Mechanisms

1 Introduction

Renewable energy sources, particularly wind and solar power, have entered an era of grid parity, signifying their competitive cost against conventional energy (Oskouei & Mohammadi-Ivatloo, 2020; Wang, Hasanefendic, Von Hauff, & Bossink, 2022; Yan, Yang, Elia Campana, & He, 2019). Consequently, the effective market integration of renewables emerges as a pivotal issue in policy-making and academic research (Hu, Harmsen, Crijns-Graus, Worrell, & van den Broek, 2018). Yet, this transition presents marked market challenges, especially during large-scale integration. The inherent intermittency and non-dispatchability of wind and solar power progressively diminish their market value, reflecting the intricate dynamics of renewables in the market and their profound impact on pricing structures (Hirth, 2013; Hirth, Ueckerdt, & Edenhofer, 2016).

Prior studies have found that with the increasing share of variable renewable energies in the electricity market, market prices generally show a downward trend(Brown & Reichenberg, 2021; Eising, Hobbie, & Möst, 2020). This is largely due to the extremely low or near-zero marginal costs of wind and solar power generation, gradually displacing more expensive traditional generators (Hirth, 2013). Market prices are often determined by the marginal cost of the last generator meeting demand, thus during peak wind and solar generation, market prices are driven down. This price reduction, especially for wind and solar generators, is known as the "Revenue Cannibalization Effect", where their highest output coincides with lowered prices (Liebensteiner & Naumann, 2022; Oskouei & Mohammadi-Ivatloo, 2020).

As of 2022, Japan's solar installation capacity surged to 83 gigawatts, surpassing natural gas to become the most widely installed generation technology[1]. This milestone underscores a significant shift in the country's energy landscape, reflecting Japan's ongoing transition towards renewable energy sources in its pursuit of sustainable energy policies and environmental targets. According to the Ministry of Economy, Trade and Industry (METI), solar power accounted for 8.3% and wind power for 0.9% of Japan's energy market share in 2022. However, with the significant deployment of renewable energies, the occurrence of the Revenue Cannibalization Effect in its electricity market is a subject of investigation. This study will first conduct an analysis using historical data to examine the specific impact of renewable energies on the electricity market. Then, we will explore the evolutionary dynamics of solar and wind power within

---

[1] 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.

Japan's electricity market and assess their influence on market in the long run.

1.1 The Impacts of Renewable Energy’s Integration to Japan's Electricity Market

The variability of renewable energy output has significantly impacted the supply and demand balance in Japan's electricity market. According to the ISEP report (2023), in 2022, at certain times, the output from variable renewable energy sources constituted up to 69% of Japan's total electricity consumption. A notable instance, sourced from the same report, occurred on May 4, 2022, at 11 AM, when solar power generation in the Kyushu region exceeded the total regional electricity demand by 4.9%[2].

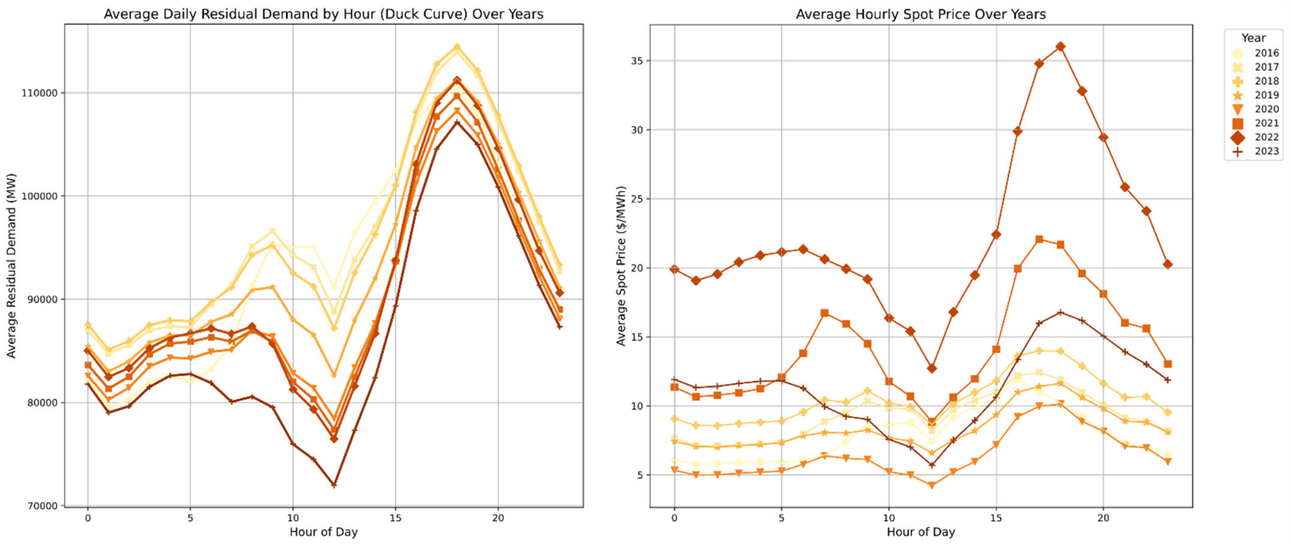

Figure 1 “Duck Curve” and “Peak Shifting” phenomena in the national power market in Japan

Note: The vertical axis represents the residual electricity demand (in MWh, left panel) and the system price in JPEX(in JPY/kWh, right panel), and the horizontal axis shows different times of the day. The graph uses line colors to differentiate each year's residual demand patterns. The solar icon depicts the daytime impact of solar power generation, which is the duck-shaped curve.

Data source: Japan Electric Power Exchange (JEPX)

As it continues to manifest, the 'Duck Curve' phenomenon in the residual electricity demand has become increasingly pronounced. The Duck Curve represents a curve that shows the difference between solar output and overall regional electricity demand throughout the day, i.e., the residual demand. This phenomenon poses potential challenges to the flexibility of traditional power systems and has significant implications for the electricity market. The accompanying diagram illustrates a noticeable trend of rising electricity prices during early morning and evening peak

---

[2] ISEP (2023). "2022 Share of Electricity from Renewable Energy Sources in Japan (Preliminary)." Retrieved from https://www.isep.or.jp/en/1436/, accessed on December 6th, 2023.

hours. This surge in power prices during these peak periods is known as the 'Peak Shifting' phenomenon, reflecting the dynamic interplay between renewable energy input and demand-driven electricity pricing in modern electricity markets.

The left panel of Figure 1 demonstrates the "Duck Curve" phenomenon in Japan's electricity market from 2016 to 2022. The figure clearly illustrates that, with each passing year and increased solar power generation, there is a progressive decrease in daytime residual demand, followed by a rapid increase towards the evening. This trend, particularly pronounced in 2022, suggests a significant rise in solar power generation. The reduction in solar power at the early evening peak necessitates other power sources to meet demand, creating this distinctive demand pattern.

The right panel in Figure 1 illustrates the trends in electricity prices (in Yen/kWh) across various times of the day from 2016 to 2022. Notably, there was a significant increase in electricity prices during the evening hours, especially in 2021 and 2022, with a peak nearing 30 Yen/kWh in 2022. In contrast, from 2016 to 2020, the prices in this period were relatively stable with minor fluctuations. During the day, particularly around noon, a downward trend in prices was observed, likely due to the high output of solar power increasing the electricity supply, thus lowering the price. This graph effectively showcases how electricity prices evolve over time and with changes in renewable energy production, highlighting the impact of market supply and demand dynamics on pricing.

1.2 Declining Market Value of Solar Output

Figure 2 illustrates the relationship between the penetration rate of photovoltaic (PV) output and the unit revenue of PV stations in the wholesale electricity market from 2016 to 2023. The unit revenue is calculated using a weighted average price method, multiplying each hour's solar power generation by the market price at the same hour to determine hourly solar power revenue[3]. This is then summed across all hours in a week and divided by the total solar generation of that week to yield the weekly average revenue per kWh of solar power. The findings indicate a significant downward trend in the unit revenue of PV stations as the PV output penetration rate increases from 2.5% to 20%, falling from around 10 Yen/kWh to less than 5 Yen/kWh. The decline is more pronounced when excluding the impact of the 2022 Ukraine conflict-induced natural gas price rise on wholesale prices. This analysis reveals the increasing revenue pressure on PV stations as their capacity in the power market grows.

---

[3] The unit revenue calculations in this study assume renewable energy sources, such as solar and wind power, trade in the electricity wholesale market. This theoretical scenario contrasts with the current practice in Japan, where a significant portion of renewable energy is compensated at the Feed-In Tariff (FIT) rate, not through market transactions. This assumption is made to explore the potential market dynamics and economic viability of renewable energy under full market integration.

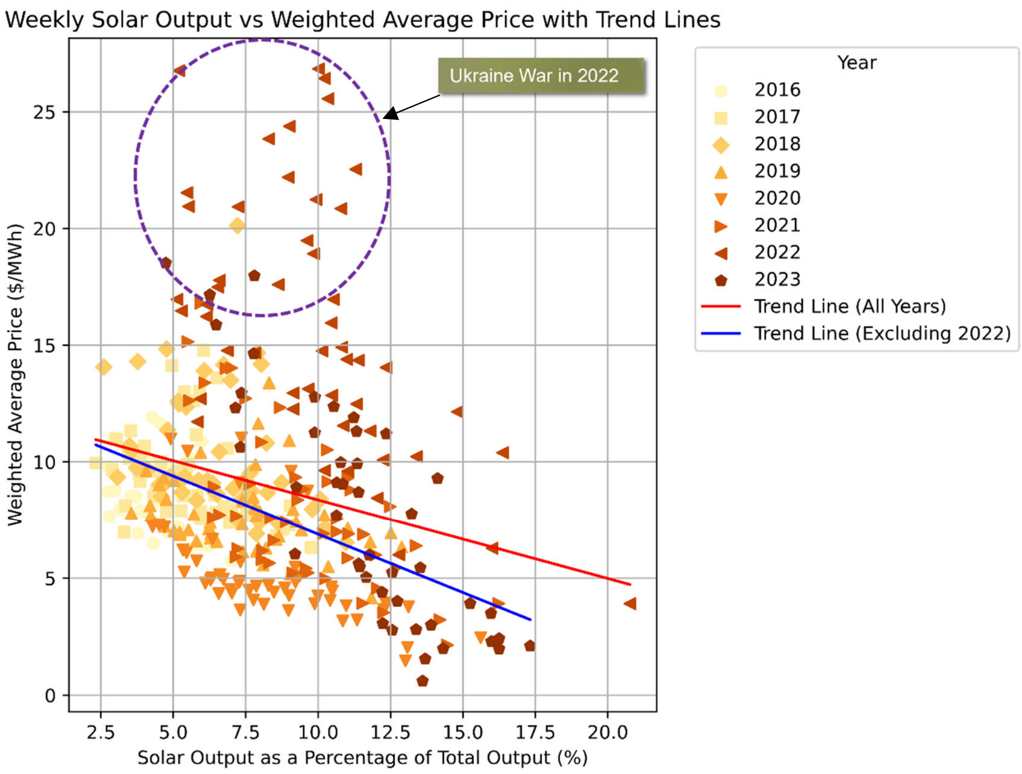

Figure 2 Weekly Solar Output Penetration and Wholesale Electricity Market Pricing Dynamics

Data source: Japan Electric Power Exchange (JEPX)

1.3 Market Value of Wind Output

Figure 3 shows that between 2016 and 2023, the proportion of wind energy in Japan's total electricity generation displayed fluctuations but no significant upward or downward trends, contrasting with photovoltaic power. Despite some influence of wind output variability on the revenue per unit of electricity for wind farms, it didn't exhibit the substantial negative correlation seen in PV power. A pertinent reason for the muted presence of the Revenue Cannibalization Effect in wind energy within Japan's market may be attributable to the overall smaller installed capacity of wind power. With wind power's generation output accounting for less than 2% of the total, its impact on the market is currently not as pronounced as solar energy. This smaller scale of wind energy generation, in contrast to solar power, means that its influence on market dynamics, particularly in terms of revenue volatility, remains relatively limited at this stage in Japan's electricity market.

To sum up, the above historical review of solar energy development in Japan reveals a declining trend in market value with increasing market penetration. This observation raises a crucial question about the long-term trajectory of this trend. The subsequent parts of this study aim to construct a long-term simulation model to deeply analyze this phenomenon, exploring the future role and economic viability of renewable energy in the electricity market.

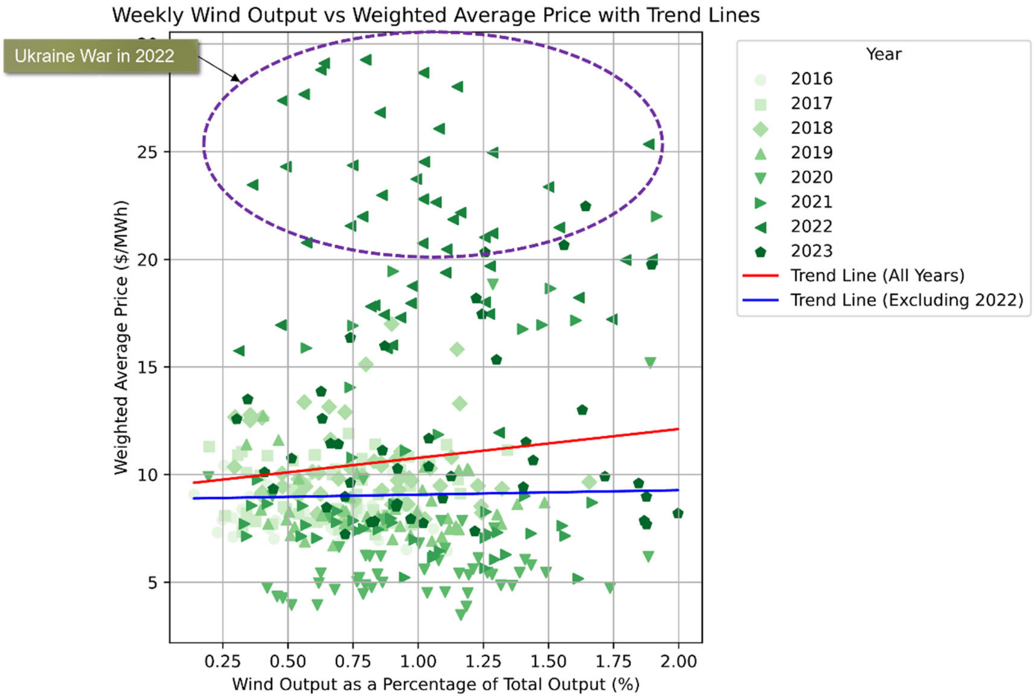

Figure 3 Weekly Wind Output Penetration and Wholesale Electricity Market Pricing Dynamics

Data source: Japan Electric Power Exchange (JEPX)

2 The PyPSA-Japan-2050 Model

In this study we build an optimal dispatch model named the PyPSA-Japan-2050 model in order to explore the long-term Revenue Cannibalization Effect in the Japanese electricity market, Our model is based on the open-source PyPSA package, which is a widely used tool in analyzing power systems and markets, particularly for integrating renewable energy(Hörsch, Hofmann, Schlachtberger, & Brown, 2018; Parzen et al., 2022). It employs an optimal power dispatch model, focusing on minimizing electricity generation costs while adhering to system constraints like demand, capacity, and stability. This approach is crucial for long-term planning in power economics, handling variable capacities and demand fluctuations(Brown, Hörsch, & Schlachtberger, 2017). The model's importance is underscored by its application in key studies, where it addresses the complexities of renewable integration and grid management.

The optimal power dispatch model, a constrained optimization problem, aims to balance the power system efficiently and economically. The following equation outlines the multi-period cost function:

$$\sum_{n,s} c_{n,s}\overline{g_{n,s}} + \sum_{n,s} c_{n,s}\overline{h_{n,s}} + \sum_{l} c_l F_l$$

$$+\sum_{t} w_t \left[\sum_{n,s} o_{n,s,t} g_{n,s,t} + \sum_{n,s} o_{n,s,t} h_{n,s,t}\right] + \sum_{t} \left[suc_{n,s,t} + sdc_{n,s,t}\right]$$

The cost function spans multiple periods, capturing the dynamic nature of electricity generation costs over time. This function integrates various cost components, operational costs $\sum_{n,s} c_{n,s}\overline{g_{n,s}}$, fuel expenses $\sum_{n,s} c_{n,s}\overline{h_{n,s}}$, and potential emissions-related charges $\sum_{l} c_l F_l$. It is structured to reflect the total cost of electricity generation by aggregating these elements, thereby offering a nuanced understanding of how costs evolve and impact the energy market over different temporal stages. This formulation is particularly relevant for analyzing long-term trends and shifts in the power generation sector.

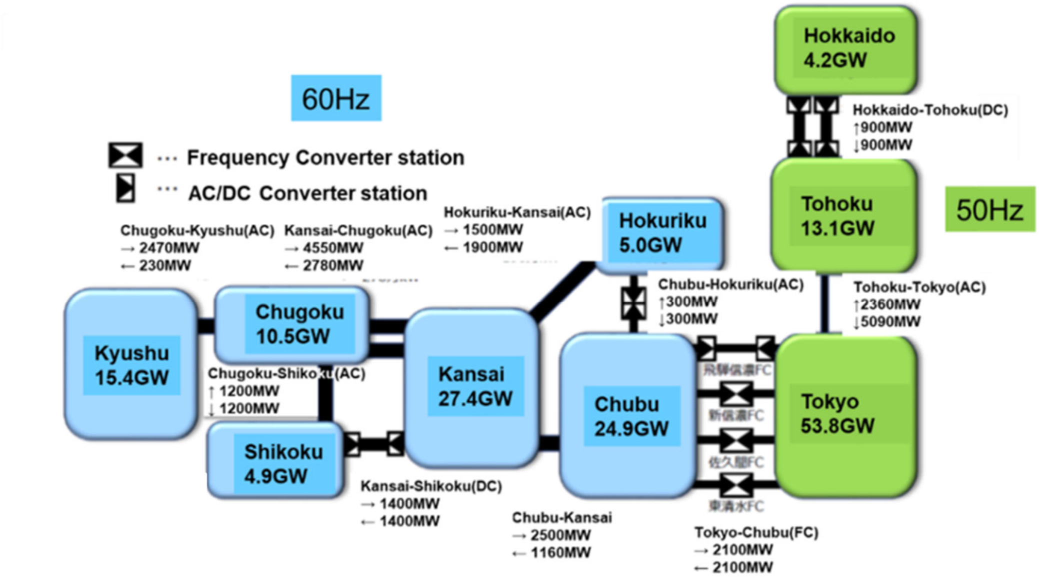

Figure 4 The basic structure of electricity network in Japan

Source: Agency for Natural Resources and Energy

https://www.meti.go.jp/shingikai/enecho/denryoku_gas/saisei_kano/pdf/035_02_00.pdf

2.1 The Scope of the Model

Our model represents an integrated energy market composed of nine dispatch regions in Japan, connected by twelve interregional transmission lines(Figure 4). This interconnected framework forms the backbone of Japan's electricity market, underpinning the government's power planning and policy decisions. Rather than operating in isolation, these regions work in concert to ensure a stable and efficient distribution of electricity. The structure of these nine regions is central to the development of energy policies and the strategic direction of Japan's energy future, facilitating the country's transition to a more sustainable and resilient power system.

The time frame extends up to 2050, with 2023 as the base year. For years leading up to 2030, we adhered to the Japanese government's mid-term targets for the power system and renewable energy development. By contrast, for the period from 2030 to 2050, our model incorporates authoritative forecasts such as the capital and operations and maintenance (O&M) costs of renewables. This approach ensures that the model accurately reflects Japan's power market operations and effectively assesses the comprehensive performance and potential value of renewable energy in the market.

2.2 Renewable Energy Development Planning

In setting the baseline scenarios for renewable energy integration, our analysis and allocation were guided by Japan's policy objectives. For solar power, we followed the Japan Solar Energy Association's 2030 target, setting a total integration goal of 125GW for residential, non-residential, and agricultural solar power. Onshore wind power allocations were based on data from the Wind Power Association, distributed across various regions. Offshore wind targets were set in line with the "Offshore Wind Industry Vision 2030," with distribution across different areas. These settings help assess the capacity and distribution of solar and wind power in each region and the impact of these policies on the overall power system and market structure. Additionally, long-term goals such as renewable energy development plans for 2030, 2040, and 2050 were considered, along with their contributions to greenhouse gas emission reduction and meeting electricity demand.

2.3 Electricity Demand Forecasts

In this study, guided by the forecasts in the IPCC's Sixth Assessment Report(Sakamoto, 2023), we examined the evolution of Japan's future energy demand. Our focus was on how electrification and sector coupling are transforming energy demand patterns, especially in the residential, industrial, commercial, and transportation sectors. As shown in Figure 5 (left), with the progress of electrification, the electricity demand in the transportation sector has significantly increased, soaring from 1,730 TWh in 2020 to nearly 20,000 TWh by 2050. Additionally, electricity consumption in the industrial, commercial, and residential sectors also shows a steady growth trend, mainly driven by the increased demand from electrification.

We also utilized hourly regional electricity demand data provided by Japan's nine major electric power companies for the year 2020. From this, we forecasted detailed hourly electricity demands for Japan from 2023 to 2050. This data enabled us to construct models of future electricity demand for each region at different times, ensuring accurate capture of the temporal variations in electricity consumption. This offers a solid data foundation for assessing future electricity supply strategies and energy policy adjustments, allowing for in-depth analysis of the dynamics of electricity market demand.

2.4 Fossil Fuel Phase-out Settings

The Japanese government has committed to halting the construction of new coal-fired power stations and gradually reducing dependence on coal energy, yet a specific phase-out timetable has not been established. In April 2023, at the G-7 Environment and Energy Ministers Meeting held in Sapporo, ministers from participating countries pledged to accelerate the phasing out of fossil fuels like natural gas to achieve net-zero greenhouse gas emissions by 2050, but no definitive end date for coal power usage was set. As the host nation of the meeting, Japan maintained a cautious stance on setting a specific timeline for phasing out coal, considering its reliance on coal energy at least for the majority of the 2030s. Therefore, we assume that coal-fired power plants will be gradually decommissioned following the end of their operational lifespans.

2.5 Cross-regional Transmission Line Reinforcements

The Japanese Ministry of Economy, Trade and Industry has recently proposed a plan for constructing an undersea power transmission line. This project aims to connect Hokkaido with the Tokyo metropolitan area via the Sea of Japan, thereby enhancing the electricity transmission capacity between these two regions. The planned transmission line is expected to have a capacity of 2 million kilowatts, equivalent to the output of two nuclear power stations. Currently, the interconnection line capacity between Hokkaido and Honshu is just 900,000 kilowatts. The long-term plan is to increase this capacity to 1.2 million kilowatts by the fiscal year 2027. The construction of this undersea transmission line is projected to boost the current power transmission capacity by 3.5 times and is scheduled to become operational in the early 2030s (See Figure 5, right panel).

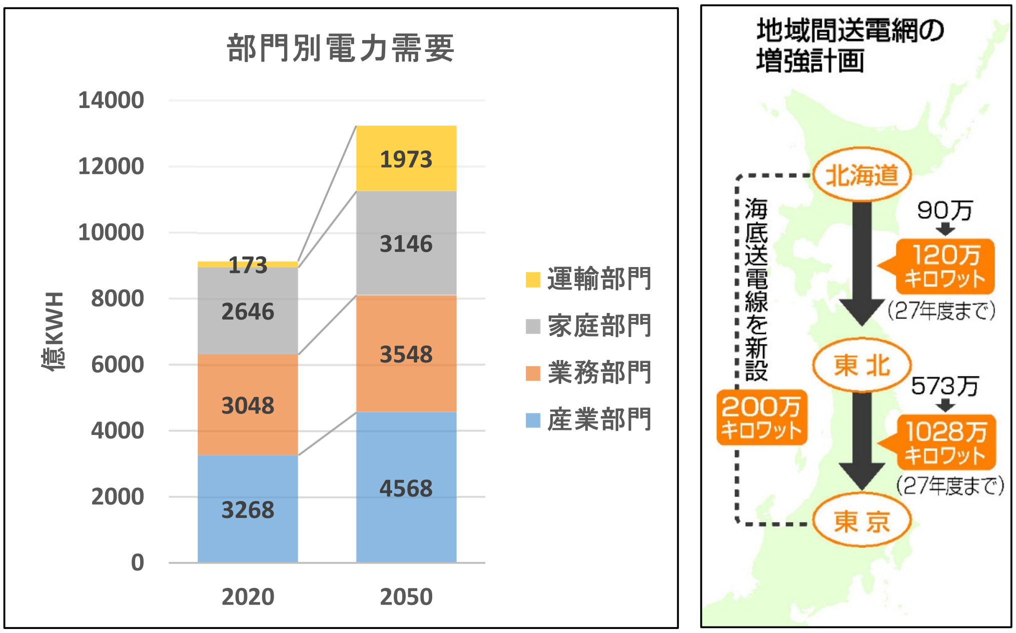

Figure 5 Demand Forecasts (left panel) and Transmission line reinforcement plan (right panel)

2.6 Flexible Sources

In this study, flexible energy sources are primarily provided through two key methods: (1) Pumped Hydroelectric Storage: This method involves using excess electricity during periods of low demand to pump water to higher elevations, which is then released to generate electricity during periods of high demand. Pumped hydroelectric stations provide additional power during peak electricity demand and help balance the grid when demand is low. (2) Electric Vehicles (EVs): Electric vehicles serve not only as transportation means but also as flexible loads and storage units for the power grid. Through smart charging technologies, EVs can charge during times of abundant electricity supply and feed electricity back to the grid during high-demand periods, playing a crucial role in balancing grid loads.

The integration of these flexible energy sources is vital for balancing the fluctuations in power supply caused by renewable energy sources. They enhance the stability and efficiency of the power system, especially in scenarios with high proportions of renewable energy integration. By judiciously utilizing these flexible sources, the power system can be effectively supported to maintain stability and efficiency while meeting the ever-changing electricity demands.

3 Theory and Scenario Settings

The definition of market average price for each generation technology is described by Formula (1). This formula illustrates the calculation of the market average price $\bar{p}^{tech}$ for a specific technology (tech) using a weighted average method. Here, g_t^{tech} represents the electricity generation by the technology at time t, and p_t is the corresponding market price at that time. The numerator calculates the total revenue generated by the technology across all time periods, while the denominator is the total electricity generation by the technology in the same time frame.

$$\bar{p}^{tech} = \frac{\sum_{t=1}^{T} g_t^{tech} * p_t}{\sum_{t=1}^{T} g_t^{tech}} \tag{1}$$

The market value ($MarketValue^{tech}$) of a specific technology is defined as the discounted value of its average market price ($\bar{p}_y^{tech}$) over time. This formula incorporates the concept of time value of money, where γ represents the time horizon and i is the discount rate. The market value is calculated by discounting the average market price for each year at the discount rate and then summing these values over the time period. This definition allows for the assessment of the overall market performance of different technologies, taking into account the time value of money, thereby providing a more comprehensive evaluation of their long-term economic viability.

$$MarketValue^{tech} = \sum_{y=1}^{\gamma} \frac{\bar{p}_y^{tech}}{(1+i)^y} \tag{2}$$

According to Brown and Reichenberg (2021), through solving the Kuhn-Tucker Conditions of the cost-minimization problem, the following first-order condition holds under the condition of a fully competitive market equilibrium:

$$MarketValue^{tech} = LCOE^{tech} \tag{3}$$

This equation states that in a fully competitive market, the market value ($MarketValue^{tech}$) of a given technology is equal to its levelized cost of electricity ($LCOE^{tech}$). The levelized cost of electricity represents the average cost per unit of electricity generated over the lifetime of the technology, taking into account all relevant costs such as capital, operation, maintenance, and fuel costs. This equilibrium condition reflects the point at which the revenue from electricity generation matches the costs, leading to a situation where no technology earns extra profits over the long term in a fully competitive market.

Similarly, according to Brown and Reichenberg (2021),in the presence of a carbon tax, the following first-order condition should be satisfied:

$$MarketValue^{tech} = LCOE^{tech} + e^{tech} * p^{carbon} \tag{4}$$

In this equation, e^{tech} is the emission intensity (e.g., tons of CO2 per MWh) of the technology, and p^{carbon} is the price of carbon (e.g., per ton of CO2). This condition indicates that the market value of a technology, when accounting for carbon pricing, should equal its levelized cost of electricity plus the additional cost imposed by its carbon emissions multiplied by the carbon price. Essentially, this integrates the external cost of carbon emissions into the economic evaluation of different electricity generation technologies. It reflects the economic principle that incorporating environmental externalities into market prices can lead to more efficient and sustainable energy production choices.

4 Baseline Results

Building upon the model settings reported in the previous sections, this chapter presents the results of the baseline scenario from the PyPSA-Japan-2050 model.

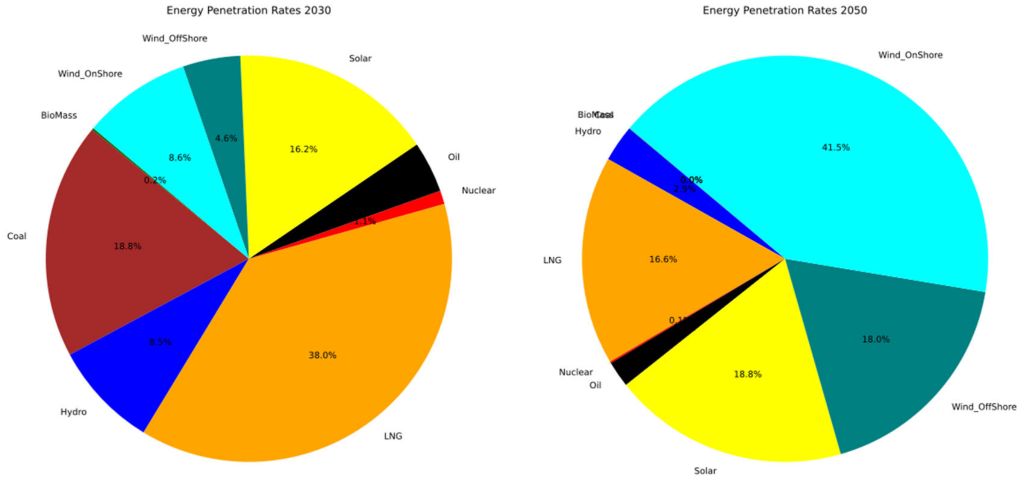

Figure 6　Electricity Mix Forecast in 2030 and 2050

Figure 6 illustrates the simulated results from our Python Japan-2050 model for the years 2030 and 2050 regarding Japan's electricity mix. It is evident from our baseline model scenario that in the year 2023, renewable energy sources such as solar photovoltaic and onshore wind generation contribute to approximately 30% of the energy mix, which is in line with mid-term target by the government. By the year 2050, the proportion of renewable energy is projected to increase further, with the largest share being attributed to onshore wind power, accounting for 41%, while the share of offshore wind power is also significant, similar to solar energy, at around 18%. Consequently, the overall proportion of renewable energy sources is expected to reach close to 80%.

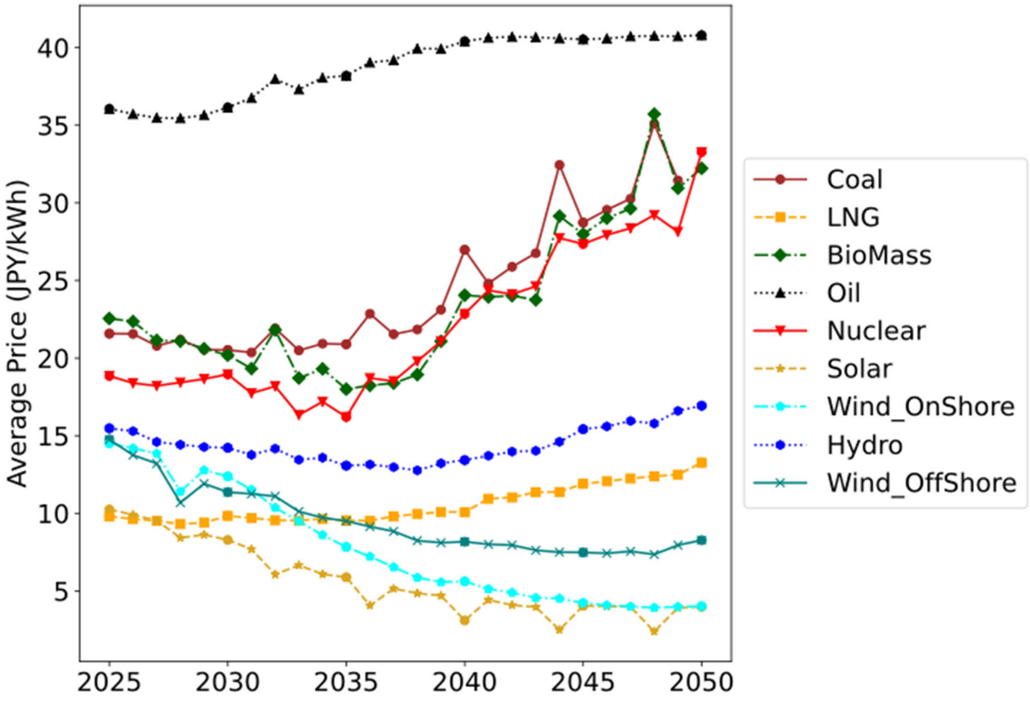

Figure 7 Yearly Average Market Price Trajectories from 2025 to 2050 for all generation techs

We are more concerned on the change of market prices for different generation technologies. Figure 7 depicts the evolution of average market prices for different types of electricity generation from 2025 to 2050. It reveals a consistent decline in the market prices for solar and both onshore and offshore wind energy, although the dynamics and rates of this decrease vary. Conversely, the average market prices for conventional energy sources are on an upward trend due to two main factors: an anticipated increase in overall electricity demand by 2050 and a rise in the cost of traditional energy sources within the same timeframe. These trends indicate that with the large-scale grid integration of renewable energy, the market's demand, and pricing expectations for dispatchable and flexible generation sources are likely to increase.

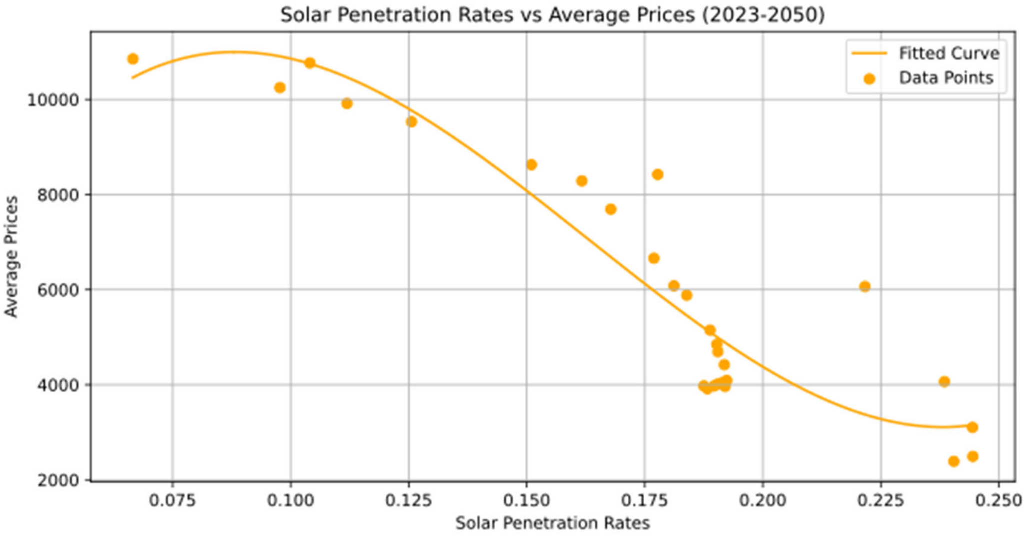

Figure 8 Solar Penetration and Average Market Prices (2023-2050)

Figure 8 demonstrates a significant downward trend in the average market price of solar energy as its penetration in the electricity market increases. Specifically, as solar energy's market share grows from 7.5% to 25%, its average market price drops from approximately 10 JPY/kWh to around 3 JPY/kWh. The fitted curve reveals that the rate of decline in solar energy's market value accelerates with increased penetration, particularly noticeable when the market share exceeds 10%. The decline slows down slightly once it surpasses 20%. This trend underscores the challenges solar energy faces in maintaining its economic competitiveness in the market as its presence grows.

In the context of electricity markets, the long-term supply curve is more complex than in traditional competitive markets. While conventional markets feature a horizontal long-term supply curve indicating equilibrium at zero profit, electricity markets exhibit a stepped merit-order curve. This reflects the varied costs of generation technologies. As renewable energy enters the market, initially there's a high supplier surplus due to their low marginal costs, but as their penetration grows, the market price often matches the marginal cost of renewables themselves, leading to a reduction in the supplier surplus for renewable energy. This shift highlights the distinct characteristics of energy market equilibria, contrasting sharply with the standard zero-profit condition of long-term equilibria in conventional markets.

5 The Impacts of Carbon Pricing

In light of the imperative to combat climate change and its adverse effects, carbon pricing, through mechanisms such as emissions trading schemes and carbon taxes, is increasingly being recognized and implemented globally as a critical strategy towards the decarbonization of economies. Tracing back to Pigou's foundational work, carbon pricing is designed to internalize the negative externalities of greenhouse gas emissions by assigning a cost to the release of CO2 and other greenhouse gases(Brown & Reichenberg, 2021). Japan's electricity market is also moving towards decarbonization with the phased introduction of a carbon trading scheme aimed at achieving carbon neutrality by 2050.

Through integrating the cost of emissions into production costs and incentivizing all energy producers to reduce emissions, carbon pricing affects high CO2-intensity power plants more significantly, altering the merit order curve and leading to higher electricity prices when fossil-fueled plants are the marginal production units, thereby increasing the market value of renewable energy(Liebensteiner & Naumann, 2022).

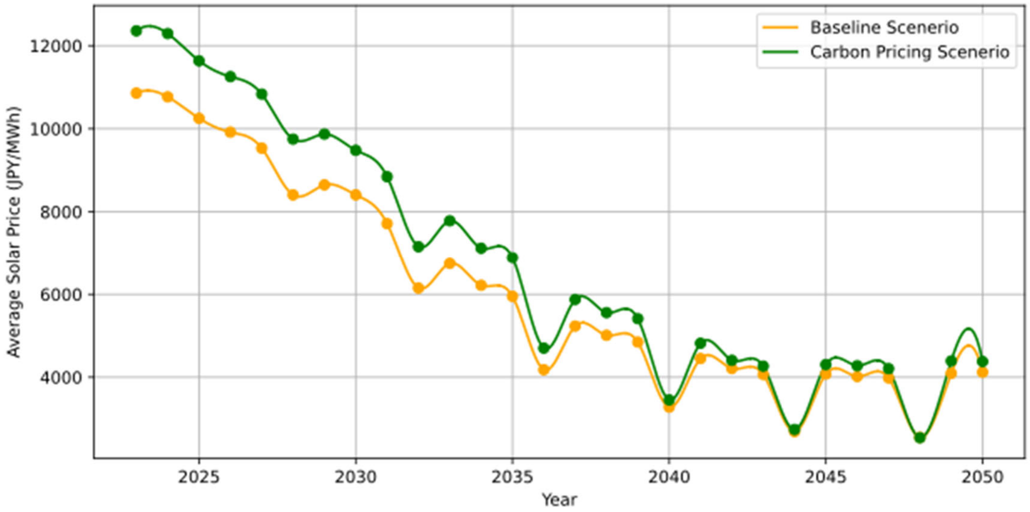

Figure 9 Comparison of Solar Market Prices under Carbon Pricing Policy with the Baseline Scenario

Figure 9, Figure 10 and Figure 11 juxtapose the market values of solar photovoltaic, onshore wind, and offshore wind energy under a carbon pricing policy scenario against our baseline scenario. These illustrations reveal that the market values of all three renewable energy sources diminish as their market penetration rates increase, owing to their variability. It is observed that in 2025, when the utilization of fossil fuels is still widespread, the carbon pricing policy significantly boosts the market value of renewable energies. However, as time progresses and the use of fossil fuels declines, particularly with the gradual decommissioning of coal-fired power units, the impact of carbon pricing policy on the market value of renewable sources diminishes and even gradually dissipates.

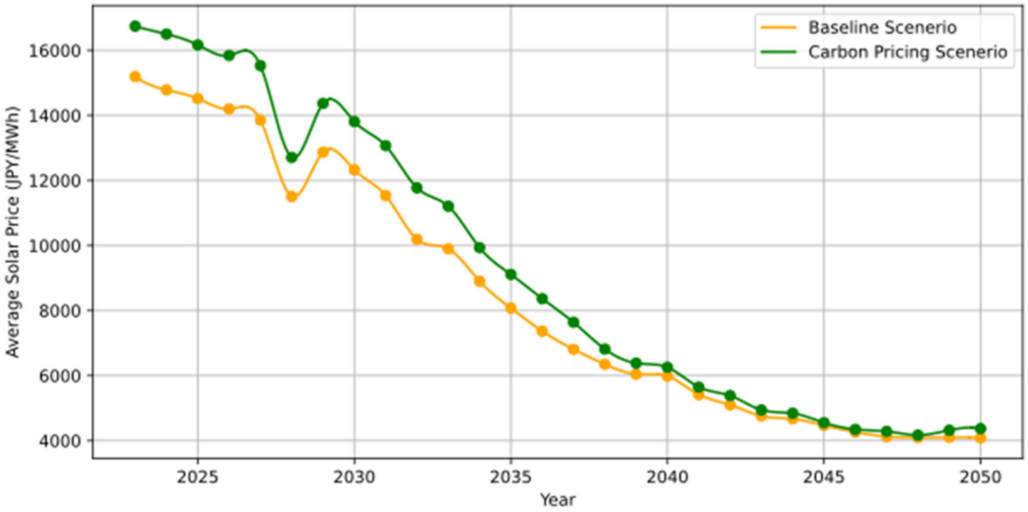

Figure 10 Comparison of On-shore Wind Market Prices under Carbon Pricing Policy with the Baseline Scenario

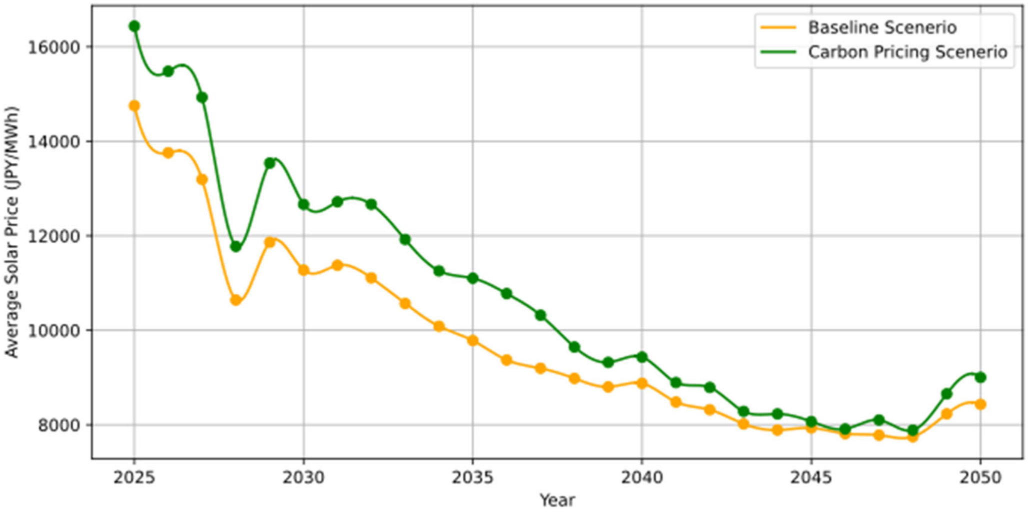

Figure 11 Comparison of Off-shore Wind Market Prices under Carbon Pricing Policy with the Baseline Scenario

6 The Impacts of Demand Response: Case of EV Batteries

Theoretically, the implementation of demand response measures, such as integrating electric vehicles (EVs) into the power system, has the potential to mitigate the decline in market value caused by increased penetration of renewable energy. EVs can be charged during periods of abundant and lower-priced electricity supply, and reduce charging or even feed electricity back to the grid during peak demand times, thereby balancing the supply and demand in the power system. This not only enhances the flexibility of the power system but also helps stabilize market prices and alleviate the "Revenue Cannibalization Effect" generated by renewable energy sources.

As depicted in Figure 12, the participation of electric vehicle (EV) batteries as a demand response tool in the electricity market leads to significant changes in the market price of solar power. The yellow curve reflects the trend of solar energy market prices without EV battery demand response, while the green curve represents the scenario with EV battery demand response in play. The chart demonstrates that in the initial stages, when solar penetration is low, the storage capability of EVs significantly enhances the market value of solar power, approximately by two yen per kilowatt-hour. However, as the proportion of solar energy in the power mix increases, this price advantage gradually diminishes, underscoring the critical role of demand response in maintaining the market competitiveness of renewable energy sources.

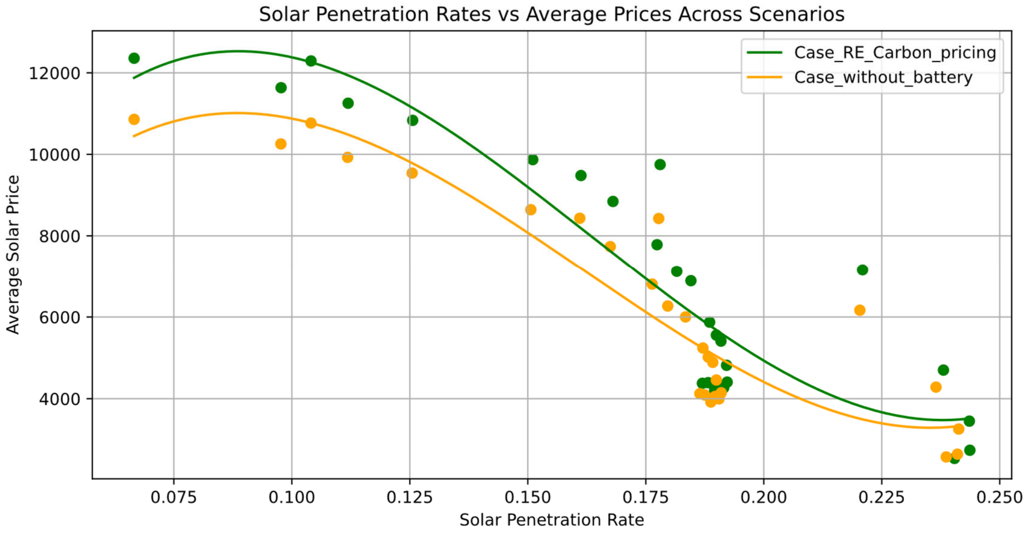

Figure 12 Solar Market Value and Penetration: The Impact of Electric Vehicle Demand Response

Figure 13 illustrates the optimal dispatch of Japan's electricity market on October 6th and 7th, 2050, as simulated by the PyPSA model. In the dynamics of the 2050 electricity market, we observe a significant impact of large-scale solar power generation under favorable weather conditions on grid scheduling. Particularly on days with abundant solar radiation, the high output from solar generation not only drives the energy absorption of pumped hydroelectric storage facilities but also fully utilizes the storage capabilities of electric vehicle (EV) batteries. This effectively mitigates the curtailment issues caused by excess solar capacity, essentially enhancing the market value of solar energy. Furthermore, during peak periods, such as morning and evening peaks, the discharge function of EV batteries helps to reduce peak electricity prices, decreasing the market value of reliance on traditional generation technologies like natural gas, thereby alleviating the overall electricity burden.

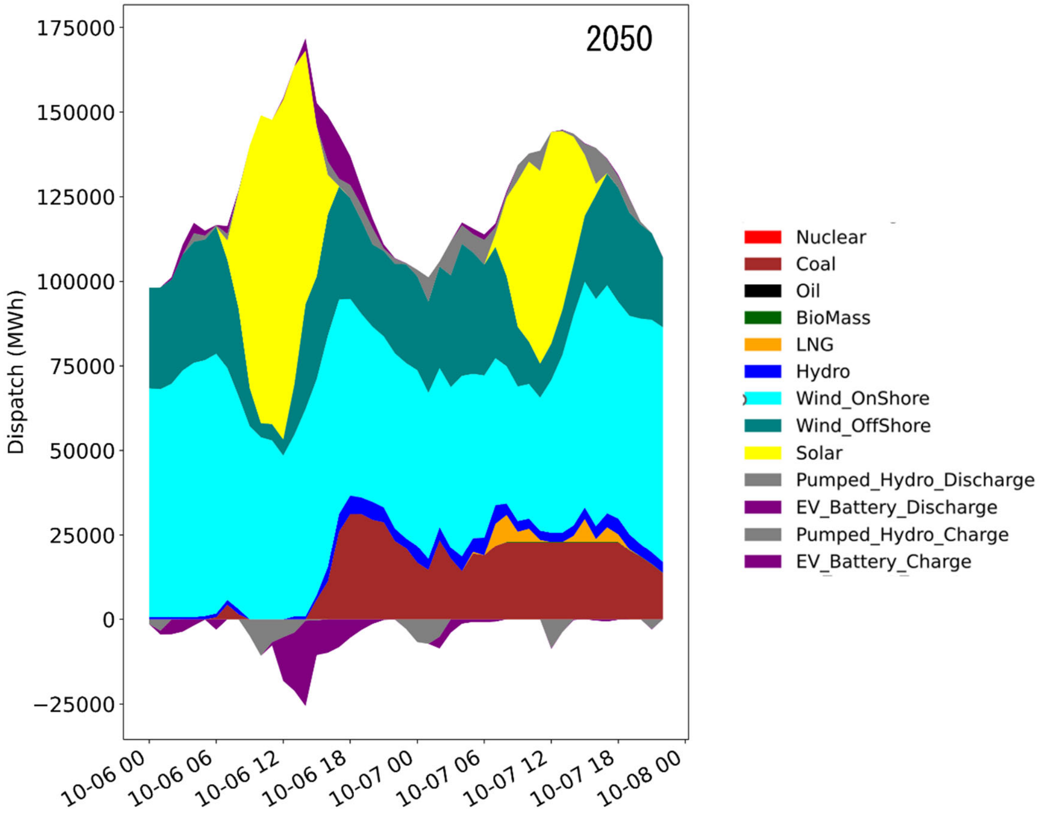

Figure 13 Demand Response in 2050: The roles of EV Storage on Optimal Electricity Dispatch

7 Conclusion and Policy Implications

This study embarked on addressing the critical challenge of integrating renewable energies into Japan's electricity markets while maintaining their market values, in the face of increasing penetration rates. An analytical review of historical data laid the foundation for a comprehensive understanding of the current state, revealing a concerning trend of declining market value for solar energy. This downward trajectory was observed even as solar energy attained grid parity, emphasizing the need for strategic policy interventions. Furthermore, our investigation utilized the PyPSA-Japan-2050 Model to simulate long-term market dynamics, which provided insights into the revenue cannibalization effect particularly pronounced within Japan's solar, offshore, and onshore wind sectors. The model's projections highlighted that without policy action, the growing share of renewables would likely lead to further decreases in market prices, adversely affecting the economic attractiveness of these energy sources.

This study also shifted focus to examine the influence of carbon pricing and demand response policies on the renewable energy market. Through the implementation of a carbon pricing policy, it was found that there is a significant potential to enhance the market value of renewable energies by making fossil-fuel-based electricity generation less competitive. However, the effectiveness of this policy showed a diminishing trend over time as the reliance on fossil fuels reduced and as coal power plants began to phase out. Demand response mechanisms, such as the integration of electric vehicle batteries into the power grid, were also found to be instrumental. These mechanisms help stabilize the market price of electricity and can mitigate the revenue cannibalization effect by allowing renewable energies to better match supply with demand fluctuations. Our findings confirm that both carbon pricing and demand response policies are effective tools in the quest for a sustainable energy market. However, their efficiency is not uniform and is subject to change over time and with varying market conditions. It is imperative that policy-makers and industry stakeholders consider the dynamic nature of these tools and their long-term implications on the market.

In conclusion, this paper underscores the necessity of a multifaceted approach to policy-making that includes both market-based incentives and regulatory support to ensure the successful integration and sustainability of renewable energies. The sustainable future of energy requires not only technological innovation but also adaptive and forward-thinking policy frameworks that can support the evolving energy ecosystem.

Furthermore, the study emphasizes the future perspective of renewable energy investment decisions. Investors need to focus not only on current returns but also on a forward-looking consideration of long-term market forecasts, making it a core part of their investment strategy. Particularly in light of the potential decline in the market value of solar energy due to policy interventions like Feed-in Tariffs (FiTs), understanding this long-term trend is crucial for investors. The potential downward trend in market value not only indicates uncertainty in investment returns but may also have a lasting impact on investor confidence and the overall health of the market. Therefore, a thorough analysis of market trends and understanding their impact on investment decisions is vital for guiding investments in renewable energy, ensuring its sustainability and competitiveness in the future energy landscape.

References

Brown, T., Hörsch, J., & Schlachtberger, D. (2017). PyPSA: Python for power system analysis. *arXiv preprint arXiv:1707.09913*.

Brown, T., & Reichenberg, L. (2021). Decreasing market value of variable renewables can be avoided by policy action. *Energy Economics, 100*, 105354.

Eising, M., Hobbie, H., & Möst, D. (2020). Future wind and solar power market values in Germany—Evidence of spatial and technological dependencies? *Energy Economics, 86*, 104638.

Hirth, L. (2013). The market value of variable renewables: The effect of solar wind power variability on their relative price. *Energy Economics, 38*, 218-236.

Hirth, L., Ueckerdt, F., & Edenhofer, O. (2016). Why wind is not coal: on the economics of electricity generation. *The Energy Journal, 37*(3).

Hörsch, J., Hofmann, F., Schlachtberger, D., & Brown, T. (2018). PyPSA-Eur: An open optimisation model of the European transmission system. *Energy Strategy Reviews, 22*, 207-215.

Hu, J., Harmsen, R., Crijns-Graus, W., Worrell, E., & van den Broek, M. (2018). Identifying barriers to large-scale integration of variable renewable electricity into the electricity market: A literature review of market design. *Renewable and Sustainable Energy Reviews, 81*, 2181-2195.

Liebensteiner, M., & Naumann, F. (2022). Can carbon pricing counteract renewable energies' cannibalization problem? *Energy Economics, 115*, 106345.

Oskouei, M. Z., & Mohammadi-Ivatloo, B. (2020). *Integration of renewable energy sources into the power grid through powerfactory*: Springer Nature.

Parzen, M., Abdel-Khalek, H., Fedorova, E., Mahmood, M., Frysztacki, M. M., Hampp, J., . . . Poli, D. (2022). PyPSA-Earth. A New Global Open Energy System Optimization Model Demonstrated in Africa. *arXiv preprint arXiv:2209.04663*.

Sakamoto, S. (2023). Transition of Japan's Energy System Towards Decarbonization—Commonalities and Diversity in Scenarios of the IPCC Sixth Assessment Report. *Electric Power Economics Review, 69*.

Wang, R., Hasanefendic, S., Von Hauff, E., & Bossink, B. (2022). The cost of photovoltaics: Re-evaluating grid parity for PV systems in China. *Renewable Energy, 194*, 469-481.

Yan, J., Yang, Y., Elia Campana, P., & He, J. (2019). City-level analysis of subsidy-free solar photovoltaic electricity price, profits and grid parity in China. *Nature Energy, 4*(8), 709-717.