Hedging strategy for sustainable solar power generation businesses by creating market instruments

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Outline

“Simultaneous hedging strategy for price and volume risks in electricity businesses using energy and weather derivatives”
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1. Introduction of price and volume risks for solar photovoltaic (PV) power producers whose profit or loss depends on both PV generation and electricity price.

2. Propose a methodology to construct optimal portfolios of weather and energy derivatives using non-parametric techniques called Generalized Additive Models (GAMs).

3. Empirical analysis in Japanese electricity market

4. Concluding remarks
Current situation of renewable energy in Japan

- Ratio of photovoltaic (PV) capacity has been increased rapidly


<table>
<thead>
<tr>
<th>Year</th>
<th>Hydro</th>
<th>Biomass+Geothermal</th>
<th>Wind</th>
<th>Solar</th>
</tr>
</thead>
<tbody>
<tr>
<td>2014</td>
<td>8.00%</td>
<td>0.47%</td>
<td>1.74%</td>
<td>1.90%</td>
</tr>
<tr>
<td>2015</td>
<td>8.60%</td>
<td>1.75%</td>
<td>1.75%</td>
<td>3.00%</td>
</tr>
<tr>
<td>2016</td>
<td>7.60%</td>
<td>2.12%</td>
<td>2.21%</td>
<td>4.40%</td>
</tr>
<tr>
<td>2017</td>
<td>7.60%</td>
<td>2.12%</td>
<td>2.21%</td>
<td>5.70%</td>
</tr>
<tr>
<td>2018</td>
<td>7.80%</td>
<td>2.42%</td>
<td>0.69%</td>
<td>6.50%</td>
</tr>
<tr>
<td>2019</td>
<td>7.40%</td>
<td>2.94%</td>
<td>0.76%</td>
<td>7.40%</td>
</tr>
</tbody>
</table>

- Fixed price purchase obligation

- Introduction of FIT in 2012

- Move to FIP in 2022 (Electricity market-linked selling system)
Trading of electricity in wholesale power exchange

Sellers
- Power generation companies

Electric power exchange
- Demand
- Supply

Buyers
- Electricity retailing companies

Consumers
- Supply contracts

Power transmission & distribution company

Volumes are volatile with PV outputs

$Spot(t)$

Simultaneous fluctuations of price and volume!
General principal of volume-price relationship

- Generation systems are called on in a specific order of increasing cost → Merit order

- Intersection between the demand and merit order curve provides the marginal cost to produce the exact volume of demand.

- The marginal costs of fossil fuel generation go up or down with energy prices.

- Electricity prices may change according to the energy prices.
### General principal of volume-price relationship

- Generation systems are called on in a specific order of increasing cost → **Merit order**

- **✓** Given energy prices and the capacities of generation units, an increase in demand leads to an increase in electricity prices.

- **✓** Solar and wind power generation may **change** depending on uncertain weather conditions.

- **✓** Increase in PV generation leads to a right shift in the curve, and a lower price may be achieved.
Feed-in support system in Japan

1st stage: Feed-in-tariff (FIT, 2012—present)

The power transmission and distribution company is supposed to purchase all PV generations at a fixed price and sell them in the exchange market under the amended FIT Act.

\[
\text{Sales revenue} = \text{Price} \times \text{Volume} \quad \text{(PV output)}
\]

Fixed for a certain long period.
**Price-volume risks of PV generations**

- **2nd stage: Feed-in-premium (FIP, 2022— )**

Solar PV producers are supposed to sell PV generations through a power exchange, and then, receive an additional premium on the price.

- **Sales revenue** = Price × Volume (PV output)

- Simultaneous fluctuations in price and volume!

Seek risk management tools based on derivatives contracts
What are derivative contracts?

- Contingent claims written on other security/commodity prices/indices, whose payoffs are determined by observed data in a certain period.

- Can be used as insurance purposes:
  - **Insurance**: the loss associated with the event
  - **Derivatives**: the value of the underlying price/index

- In the electricity market, a variety of derivatives may be used:
  - Weather derivatives (temperatures, radiation, rain/snow fall)
  - Energy derivatives (oil, gas, coal, electricity prices)

- Hedge instruments
A hedge is an investment that is taken out specifically to reduce or cancel out the risk in another investment.

\[ Y_t: \text{Value of an asset} \]
\[ S_t: \text{Another asset (being traded)} \]
\[ Y_t + \beta S_t: \text{Hedged portfolio} \]
Hedging CF fluctuations using derivatives

\( CF_t \): Cash flows associated with \( S_t \)

\( f_t(S_t) \): Derivative payoffs of \( S_t \) with payoff function \( f_t \) s.t. \( \text{Mean}(f_t(S_t)) = 0 \)

\( CF_t + f_t(S_t) \): Hedged cash flows

Sum up to zero on average

Minimized

Optimal hedging problem with suitable derivative contracts
Past research

- **Energy derivatives** applied to electricity market
  

- **Weather derivatives**
  
  Ginocchio (2008), Davis (2001), Platen and West (2004), and Brockett et al. (2006), Kanamura and Ohashi (2009), Yang et al. (2009), and Perez-Gonzalez and Yun (2013), Yamada et al. (2006), Yamada (2008)

- **Price-volume hedges**

  Focus of this research


Optimize **arbitrary nonlinear payoff functions** or find **optimal portfolios of derivatives** to fit **observed empirical data** and verify their **robustness**
Market transactions and data descriptions

Weather derivatives market
Energy derivatives market

Weather derivatives on radiation and temperature
Energy derivatives on fuel prices
Electricity forward

Solar PV power producer

Sell PV generation: $V_{t,h}$

Receive: $\pi_{t,h} = S_{t,h} \times V_{t,h}$

Spot electricity market

$V_{t,h}$: PV output (individual/total)

$S_{t,h}$: Spot electricity price at hour $h$ on day $t$

$\pi_{t,h}$: Revenue ($= S_{t,h} \times V_{t,h}$)

$R_{t,h}$: Solar radiation

$F_t$: Fuel price on day $t$

$T_{t,max}$: Maximum temperature

- Basic procedure
  - Construct a nonparametric prediction model with exogenous variables and time trends using generalized additive models
  - Formulate a minimum variance hedging problem and verify its hedge effect
Construction of nonparametric models

\[ \pi_{t,h} : = S_{t,h} V_{t,h} = \{g_h(t) + l_h(t)\}S_{t,h} + f_h(R_{t,h}) + c + \epsilon_{t,h} \]

Sales CF

- Smoothing spline functions reflecting seasonal and long term trends
- Radiation derivative payoff function

\[ \min_{g_h,l_h,f_h} \left\{ \sum_{t=1}^{N} \epsilon_{t,h}^2 \mid g_h, l_h, f_h \in \text{Penalized smooth splines} \right\} \]

Generalized Additive Model (GAM; Hastie and Tibshirani ’90)

- Applied for a relatively short period of data, for example, 2–3 years
- Other explanatory variables and cross variables may be added
- Estimation of a periodic function based on cyclical dummy variables
Estimation of periodic function with cyclical dummies

\[
\text{Seasonal}_t^{(0)} = -364 (-365), \ldots, 0
\]

\[
\text{Seasonal}_t^{(1)} = 1, \ldots, 365 (366)
\]

\[
\text{Seasonal}_t^{(2)} = 366 (367), \ldots, 730 (731)
\]

\[
\min \sum_{t=1}^{N} \left\{ y_t - f \left( \text{Seasonal}_t^{(1)} \right) \right\}^2 + \sum_{t=1}^{N} \left\{ y_t - f \left( \text{Seasonal}_t^{(0)} \right) \right\}^2 
+ \sum_{t=1}^{N} \left\{ y_t - f \left( \text{Seasonal}_t^{(2)} \right) \right\}^2 + \lambda \int_{-\infty}^{\infty} f(x)dx
\]
Estimation of bivariate payoff functions

\[
\min_{f_h} \left\{ \sum_{t=1}^{N} \left( \pi_{t,h} - f_h(\text{Seasonal}_t, R_{t,h}) \right)^2 + J_\lambda \right\}
\]

 Penalty on Tensor Product Spline Function

\[
J_\lambda = \int_{-\infty}^{\infty} \lambda_x \left( \frac{\partial^2 f}{\partial x} \right)^2 + \lambda_z \left( \frac{\partial^2 f}{\partial z} \right)^2 \, dx \, dz
\]

wiggleness penalties for both directions
- Seasonal and other time trend
- Radiation

Ensure the robustness of estimation while using small sample size data

Interpretation as a hedge model

\[ \pi_{t,h} = \{g_h(t) + l_h(t)\}S_{t,h} + f_h(R_{t,h}) + c + \epsilon_{t,h} \quad \cdots \text{Realized} \]

\[ \overline{\pi}_{t,h} = \{g_h(t) + l_h(t)\overline{S}_{t,h} + f_h(R_{t,h}) + c \quad \cdots \text{Predicted} \]

\( \pi_{t,h} - \overline{\pi}_{t,h} = \{g_h(t) + l_h(t)\}\{S_{t,h} - \overline{S}_{t,h}\} \]

\( + f_h(R_{t,h}) - f_h(R_{t,h}) \]

\( + \epsilon_{t,h} \) Payoff of spot electricity forward Optimized payoff of solar radiation Hedge error

\[ \min_{g_h, l_h, f_h} \left\{ \sum_{t=1}^{N} \epsilon_{t,h}^2 \mid g_h, l_h, f_h \in \text{Penalized smooth splines} \right\} \]

Minimum variance hedge based on GAMs
Empirical test

- Hourly data in Tokyo area (9 prefectures covered by TEPCO)
  - $S_{t,h}$: Spot electricity price in Tokyo area. http://www.jepx.org/market/
  - $V_{t,h}$: Total PV generation in Tokyo area. https://www.tepco.co.jp/forecast/
  - $R_{t,h}$: Solar radiation index (installation capacity weighted average). https://www.data.jma.go.jp/

- Minimum variance price-volume hedging:
  \[
  \pi_{t,h} := S_{t,h} V_{t,h} = \{g_h(t) + l_h(t)\} S_{t,h} + f_h(R_{t,h}) + c + \epsilon_{t,h}
  \]

- Electricity forward and radiation derivatives provided in this research in comparison with electricity forward or radiation derivatives only

Learning period (In-sample): April 1, 2016—March 31, 2019
Test period (Out-of-sample): April 1, 2019—December 31, 2019
Out-of-sample result of the hedge

- Comparison of Hedged CFs with Unhedged CFs and VRRs

**Hedged vs. Unhedged CFs**

Unhedged CF (mean adjusted)

\[
\frac{\text{Var(\text{Hedged CF})}}{\text{Var(\text{Unhedged CF})}} = 15.0\%
\]

Hedged CF

**Hedge effects based on VRRs**

- Calendar trend only (93.0%)
- Electricity forward (56.3%)
- Rad. Derivatives (54.8%)
- Electricity forward + Rad. Derivatives (18.7%)

VRR: Variance Reduction Rate

CF fluctuation measured by its variance is reduced by 85.0%
Hedging revenue from individual solar systems

$S_{t,h}$: Power output of an individual solar system in Hiroshima City

$WTI_t$: Oil price, $T_{t,max}$: Daily maximum temperature

\[ \pi_t = \sum_{h} S_{t,h} V_{t,h} = g(t) + \beta \cdot WTI_t + \varphi(t, R_t) + \psi(t, T_{t,max}) + \varepsilon_t \]

Daily CF

1. Calendar trend (base, day, cyclic)
2. Lagged WTI providing fuel forward payoffs
3. Radiation derivatives
4. Temperature derivatives

Learning period (In-sample): January 1, 2013—December 31, 2017
Test period (Out-of-sample): January 1, 2018—December 31, 2018

\[
\min_{g, \beta, \varphi, \psi} \left\{ \sum_{t=1}^{N} \varepsilon_{t,h}^2 \mid g, \varphi, \psi \in \text{Penalized smooth splines}, \beta \in \mathbb{R} \right\}
\]
Out-of-sample performance of the hedge

\[ \pi_t := \sum_h S_{t,h} V_{t,h} = g(t) + \beta \cdot WTI_t + \varphi(t, R_t) + \psi(t, T_{max}) + \varepsilon_t \]

(1) Calendar trend  (2) WTI  (3) Solar derivatives  (4) Temperature derivatives

In-sample: 2011-2017
Out-of-sample: 2018

The VRR is largely improved when adding solar derivatives

Across all scenarios, the VRR improved from approximately 31.3%

- Monotonically decreased even for the out-of-sample case
Conclusion

Simultaneous hedging of price and volume risks for solar power PV generation businesses by constructing derivatives/forwards contracts

Optimizes arbitrary nonlinear payoff functions or finds optimal portfolios of weather and energy derivatives to fit the observed empirical data

- Provided a methodology to construct optimal portfolios of weather and energy derivatives using non-parametric techniques called Generalized Additive Models (GAMs).

- Out-of-sample simulations illustrated that the CF fluctuations were reduced by 70—80% in terms of the VRRs.

- Note: Applied for a short period of data, e.g., 2—3 years, with other explanatory variables.

  ➡️ New retailing companies and PV owners
Research project of weather derivatives

JSPS Challenging Research (Exploratory) 19K22024
(PI: Yuji Yamada, June 2019—March 2022)

Risk management system for losses caused by trading electricity in whole sales market using weather derivatives

Collaborators: Naoki Makimoto, Setsuya Kurahashi

Faculty of Business Sciences, University of Tsukuba

Develop risk management tools for renewable energy market.

Construct prediction error weather derivatives against losses caused from prediction errors.
Trading of renewable energy

- Power transmission & distribution company may charge a penalty to compensate costs of backup generators if prediction error exists.

Need “insurance system” for loss of prediction errors.
Research project of P2P electricity trading

JSPS Grant-in-Aid for Scientific Research (A) 20H00285
(PI: Yuji Yamada, April 2020—March 2025)

Constructions of risk management tools for supporting P2P trading of renewable electricity

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