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Business-Oriented Simulation Model for a Virtual Power Plant Balancing Renewable Energy and Profitability

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ABSTRACT
The rapid deployment of renewable energy (RE) has intensified concerns about the variability of solar and wind power and the resulting difficulty of maintaining a reliable and economically viable electricity supply. This study develops a profit-enhancing business model for a Virtual Power Plant (VPP) that aggregates solar PV, wind turbines, and battery storage serving residential customers in the Kanto region of Japan. Building on and extending an existing cost structure for VPPs, we formulate a profit-based evaluation model and conduct an annual, hourly simulation using actual 2022 meteorological and demand data. A baseline analysis shows that aggressively using batteries to raise the RE share to 98% leads to a large operating deficit, highlighting a fundamental economic barrier. To mitigate this trade-off, we introduce two operational rules: a "switching price" that dynamically selects between market procurement and contracted generators, and constraints that activate battery charging/discharging only when it is economically favorable relative to the market price. Numerical experiments demonstrate that the proposed strategy achieves a 72% renewable energy ratio while maintaining positive annual profit, suggesting that appropriately designed control rules can simultaneously support RE expansion and sustainable VPP operation.

Keywords: virtual power plant, renewable energy, battery storage, electricity market.

INTRODUCTION
In recent years, reducing greenhouse gas emissions and expanding the use of renewable energy (RE) have become central global policy objectives for achieving a sustainable society [1–3]. Japan has committed to carbon neutrality by 2050 and set intermediate targets to increase the share of RE in the national electricity mix to 36–38% by 2030 and 50–60% by 2050 [2].

However, major RE sources such as solar and wind power are strongly influenced by meteorological and geographical conditions. Their inherently fluctuating output complicates the task of maintaining a stable electricity supply. As the penetration of RE increases, balancing supply and demand becomes progressively more difficult, and power systems require flexible resources that can quickly respond to sudden changes in load or generation.

A promising approach to this challenge is the Virtual Power Plant (VPP), which integrates and centrally coordinates distributed generation and storage resources [4]. In a VPP, an aggregator manages RE facilities and battery systems owned by households and businesses so that the aggregated resources can behave as a single large power plant and participate in electricity markets. As illustrated conceptually in Fig. 1, the VPP operator co-ordinates the dispatch of solar, wind, battery storage, and demand response to smooth output fluctuations and flexibly supply electricity in response to demand.

Recent studies have examined the technical challenges associated with large-scale RE integration and the role of flexibility resources. For example, Ergun et al. provide a comprehensive review of how high penetrations of solar and wind generation affect power system stability, reliability, and power quality, emphasizing that energy storage systems (ESSs) will become indispensable for maintaining flexibility and mitigating curtailment as renewable capacity grows [5]. These works underline the importance of storage and other flexible resources from a system-planning perspective, but they do not explicitly address the business feasibility of individual aggregators or retailers.

With regard to VPPs, Roozbehani et al. survey operational strategies, mathematical models, and optimization methods, including deterministic and stochastic scheduling, heuristic algorithms, and reinforcement learning approaches [6]. Their review shows that most existing models treat the VPP as an optimization problem aimed at minimizing operating cost or maximizing profit, often in idealized market settings. More recently, Abdelkader et al. discuss the evolution of VPPs into key enablers of decentralized, flexible, and sustainable power systems, summarizing real-world demonstration projects and stressing that profitability and appropriate market design are crucial for VPP deployment at scale [7]. However, the majority of these studies focus either on sophisticated optimization formulations or on European-style markets, and rarely on simple profit-enhancing operation rules calibrated to the current Japanese retail market.

In Japan, system-level analyses have evaluated countermeasures for large-scale renewable integration, such as the deployment of storage, demand response, and demand-side batteries in smart houses and buildings [8]. These studies use power system evaluation models to quantify the impact of different countermeasure portfolios on nationwide supply–demand balance and cost. While they provide important insights into the overall effectiveness of flexibility options, they do not directly examine the business model and profit structure of a VPP that aggregates distributed solar, wind, and batteries on the retail side.

Against this background, the present study contributes by developing a business-oriented simulation model of a VPP that explicitly quantifies the trade-off between renewable energy penetration and profitability under current battery cost assumptions in Japan. Instead of solving a highly complex profit-maximizing optimization problem, we focus on profit-enhancing operational rules that can be realistically implemented by an aggregator: a “switching price” for choosing between market procurement and contracted generators, and economically motivated constraints on battery charging and discharging. By evaluating these rules in an annual, hourly simulation using actual 2022 weather and demand data for the Kanto region, we show how VPP operators can support relatively high renewable energy shares while maintaining financial viability.

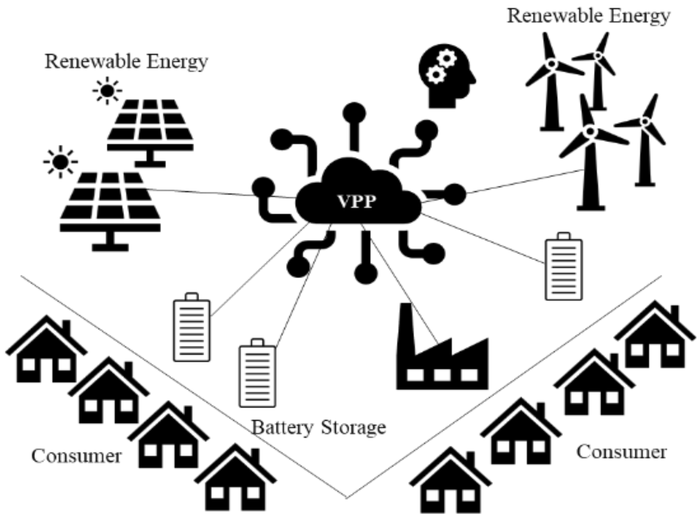

Fig 1: VPP Conceptual Diagram

MATHEMATICAL MODEL OF THE VIRTUAL POWER PLANT

This section presents the mathematical formulation of the proposed VPP model. The VPP coordinates multiple distributed energy resources to maintain the supply–demand balance while seeking to enhance profit. When electricity prices in the wholesale market are high, the VPP sells surplus generation or utilizes battery discharge to increase revenue, while during low-price periods it purchases electricity from the market and charges batteries if economically attractive. The model extends the cost structure proposed by Mengxuan Lv et al. [9] to the context of the Japanese electricity market. While [9] focused mainly on the conceptual cost components and bidding strategy of VPPs, quantitative validation was limited. In this study, we incorporate their cost categories into a profit-oriented evaluation framework and evaluate the model via numerical simulation.

The objective function is expressed as the sum of cost and revenue terms. Costs (treated as negative contributions to the objective) include:

- f_1: power purchase from contracted generators,
- f_2: battery charging and discharging,
- f_3: incentives for demand response via interruptible loads,
- f_4: wheeling (transmission) charges
- f_5: electricity procurement from the wholesale market

Revenues (positive contributions) are obtained from:

- f_6: sales of electricity to the market, and
- f_7: sales of electricity to end consumers.

Objective Function

Objective Function:

$$f = f_6 + f_7 - f_1 - f_2 - f_3 - f_4 - f_5 \tag{1}$$

$$f_1 = P_{PV} \times C_{PV} + P_W \times C_W \tag{2}$$

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$$f_2 = (\mathrm{P}_{\mathrm{k}}^{\mathrm{ess+}} + \mathrm{P}_{\mathrm{k}}^{\mathrm{ess-}}) \times C_E \tag{3}$$

$$f_3 = A_{DDR} \times C_{DDR} + A_{UDR} \times C_{UDR} \tag{4}$$

$$f_4 = A_t \times C_t \tag{5}$$

$$f_5 = A_{mp} \times C_{mup} \tag{6}$$

$$f_6 = A_{ms} \times C_{mup} \tag{7}$$

$$f_7 = A_C \times C \tag{8}$$

Let the time index be k, and consider the following main decision variables and parameters:

- P_{PV}: Amount of solar power generation
- C_{PV}: Unit cost of solar power procurement
- $\mathrm{P_W}$: Amount of wind power generation
- C_W: Unit cost of wind power procurement
- $\mathrm{P}_{\mathrm{k}}^{\mathrm{ess+}}$: Battery charging amount
- $\mathrm{P}_{\mathrm{k}}^{\mathrm{ess-}}$: Battery discharging amount
- k: Time step index
- C_E: Unit cost of battery charging/discharging
- A_{DDR}: Downward demand response amount
- C_{DDR}: Unit price of downward demand response
- A_{UDR}: Upward demand response amount
- C_{UDR}: Unit price of upward demand response
- A_t: Amount of transmitted electricity
- C_t: Average unit wheeling charge
- A_{mp}: Amount of electricity purchased from the market
- C_{mup}: Market unit price (for both buying and selling)
- A_{ms}: Amount of electricity sold to the market
- A_C: Total consumption (monthly)
- C: Electricity unit price charged to consumers

Using these variables, we define an objective function (1)–(8) that represents the total profit over the simulation horizon, calculated as total revenue minus total cost. The terms corresponding to each cost and revenue category follow the structure summarized above.

Solar Power Generation Model

Solar PV generation is modeled using the installed capacity, conversion efficiency, and solar irradiance. Let

- P_{PV}: Solar power generation amount
- A: System capacity (kW)

- H_i: Solar irradiance on day i
- r: System efficiency
- i: Index of solar power supplier
- R: Total number of solar power suppliers

The power output of solar plant i is given by (9) and (10), which compute the hourly PV generation based on A, r, and the irradiance profile H_i. The total solar generation is obtained by aggregating outputs from all PV sites. In the numerical analysis, H_i is derived from actual 2022 irradiance data [10, 11].

$$P_{PVi} = A \times H_i \times r \tag{9}$$

$$P_{PV} = \sum_{i=1}^{R} P_{PVi} \tag{10}$$

Wind Power Generation Model

Wind power generation is described by a standard piecewise function of wind speed. Let

- P_W: Wind power generation amount
- P_{Wr}: Maximum wind power generation output
- V: Wind speed
- V_i: Cut-in wind speed
- V_o: Cut-out wind speed
- V_r: Rated wind speed
- n: Index of wind power supplier
- S: Total number of wind power suppliers

Equations (11)–(14) specify that the output increases with wind speed between V_i and V_r, remains constant at P_Wr between V_r and V_o, and becomes zero below V_i or above V_o. Actual 2022 wind speed data for each site are used in the simulation [11, 12].

$$P_{wn} = 0 \; (V_n \leq V_i,\; V_n \geq V_o) \tag{11}$$

$$P_{wn} = \frac{V_n - V_i}{V_r - V_i} P_{wr} \; (V_i \leq V_n \leq V_r) \tag{12}$$

$$P_{wn} = P_{wr} \; (V_r \leq V_n \leq V_o) \tag{13}$$

$$P_W = \sum_{n=1}^{S} P_{Wn} \tag{14}$$

Battery Storage Model

Battery storage is modeled by distinguishing between attempted and actual charging/discharging amounts and by tracking the state of charge (SOC). Let

- P_k^{ess+}: Actual battery charging amount
- P_k^{ess-}: Actual battery discharging amount
- $\mathrm{P}_\mathrm{k}^\mathrm{ch}$: Attempted battery charging amount
- $\mathrm{P}_\mathrm{k}^\mathrm{dis}$: Attempted battery discharging amount
- ε: Charging/discharging efficiency
- m_k^{ess}: Battery state of charge
- Cap_{ess}: Maximum battery capacity
- k: Time step index

Equations (15) and (16) define the relationship between P_k^{ch}, P_k^{dis} and P_k^{ess+}, P_k^{ess-} through the efficiency ε. Equations (17)–(20) describe the SOC dynamics and bounds over time. Equation (21) prohibits simultaneous charging and discharging, and (22) imposes additional operational limits. Lithium-ion batteries are assumed in this study, consistent with common applications in VPPs [13].

$$P_k^{ess+} = \varepsilon \times P_k^{ch} \tag{15}$$

$$P_k^{ess-} = \varepsilon \times P_k^{dis} \tag{16}$$

$$m_k^{ess} = m_{k-1}^{ess} + (P_k^{ess+} - P_k^{ess-}) \tag{17}$$

$$0 \leq m_k^{ess} \leq Cap_{ess} \tag{18}$$

$$0 \leq P_k^{ess+} \leq \rho_k^{ess+} \times P_k^{ess+} \tag{19}$$

$$0 \leq P_k^{ess-} \leq \rho_k^{ess-} \times P_k^{ess-} \tag{20}$$

$$\rho_k^{ess+} + \rho_k^{ess-} = 1 \tag{21}$$

$$\rho_k^{ess+}, \rho_k^{ess-} \in \{0,1\} \tag{22}$$

NUMERICAL ANALYSIS

Overview of Experimental Case

We consider a VPP serving 2,000 detached households in the Tokyo area as electricity consumers. On the supply side, the VPP aggregates:

- five solar power plants of 250 kW each (total 12,500 kW), located in Tokyo, Ibaraki, Gunma, Chiba, and Tochigi;
- four wind power plants of 2,000 kW each (total 8,000 kW), located in Tokyo, Tsukuba, Maebashi, and Utsunomiya.

Key parameter settings are:

- solar power procurement cost: $c_{\mathrm{PV}} = 11\mathrm{JPY/kWh}$,
- wind power procurement cost: $c_{\mathrm{W}} = 17\mathrm{JPY/kWh}$,
- battery charging/discharging cost: $c_{\mathrm{E}} = 45\mathrm{JPY/kWh}$,

- downward demand response price: $C_{DDR} = 10\text{JPY/kWh}$,
- upward demand response price: $C_{UDR} = 5\text{JPY/kWh}$,
- average wheeling charge: $C_t = 9.92\text{JPY/kWh}$,
- PV system efficiency: $r = 0.73$,
- cut-in, rated, and cut-out wind speeds: $V_\text{i} = 3\text{m/s}$, $V_\text{r} = 12\text{m/s}$, $V_\text{o} = 24\text{m/s}$.

The hourly electricity demand per household used in the model is shown in Fig. 2. Monthly and hourly consumption profiles are based on the "FY2013 Survey Report on Actual Electricity Consumption in Households" [14].

The simulation is conducted on an hourly basis over an entire year (8,760 time steps). For each hour, the VPP is assumed to allocate generation, storage, demand response, and market transactions with the aim of enhancing profit, subject to physical and operational constraints.

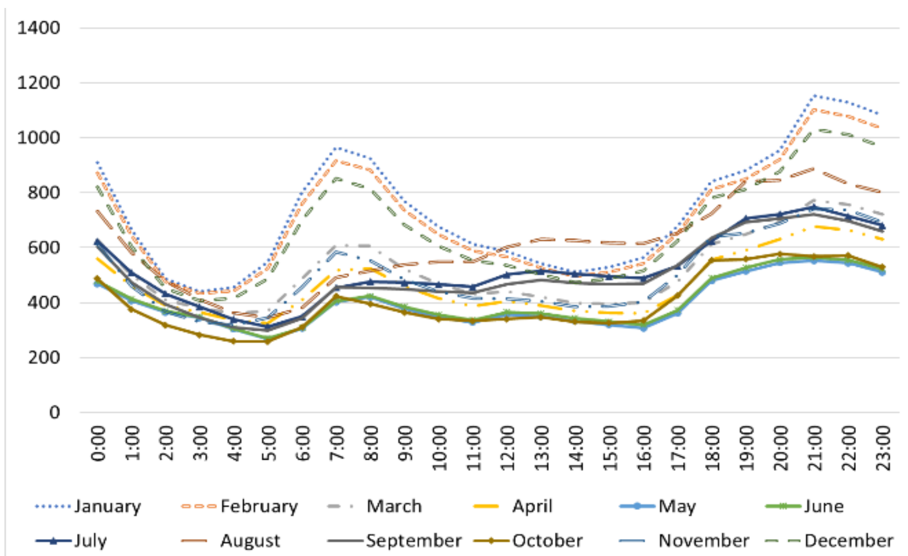

Fig 2: Hourly Electricity Demand of Consumers

Baseline Results and Comparison of Operators

Table 1: Comparison Between VPP Operator and Retail Operator (Unit: 10,000 JPY)

		Retailer	VPP Operator (Without Battery)	VPP Operator (With Battery)
Cost	Generation Cost	0	17127	17127
	Power Storage Cost	0	0	21703
	Interruptible Load Cost	0	1173	1173
	Wheeling Cost	9298	8891	8891
	Electricity Purchase Cost	24638	6290	407
	Total Cost	33936	33481	49301
Revenue	Electricity Sales Revenue (Market)	0	11593	4575
	Electricity Sales Revenue (Consumers)	34896	33251	33251
	Total Revenue	34896	44844	37826
Net Profit (Total Revenue – Total Cost)		960	11363	-11475
Renewable Energy Ratio		0%	73%	98%

Table 1 compares the cost structure, profit or loss, and RE ratio for three types of operators:

1. a retailer that supplies electricity only by purchasing from the wholesale market,
2. a VPP operator without battery storage, and
3. a VPP operator with battery storage but without additional economic constraints.

The results indicate that introducing VPP control and RE procurement substantially reduces reliance on the electricity market and can increase the renewable share. In particular, adding battery storage allows the VPP to raise the RE ratio to 98%. However, this comes at the expense of very high storage costs, which drive the total cost well above total revenue and result in a large operating loss.

In contrast, the VPP without batteries already improves both profitability and the RE ratio compared with the pure retailer: the RE share rises to around 73% and the profit exceeds that of the retailer. These findings highlight the central dilemma: batteries are effective at increasing RE penetration but, under current cost assumptions, can easily undermine the economic viability of the business.

Introduction of a Switching Price

In the baseline VPP case, the operator primarily procures electricity from contracted renewable generators, using market purchases only to cover residual shortages. However, in practice, market prices occasionally fall below the contracted prices for solar and wind power. To exploit this, we introduce a "switching price" rule that determines whether electricity should be procured from the market or from generators.

Specifically, if the market price is lower than a predefined switching price, the VPP purchases electricity from the market; otherwise, it procures from contracted generators. By varying the switching price, we investigate how profitability and the RE ratio change.

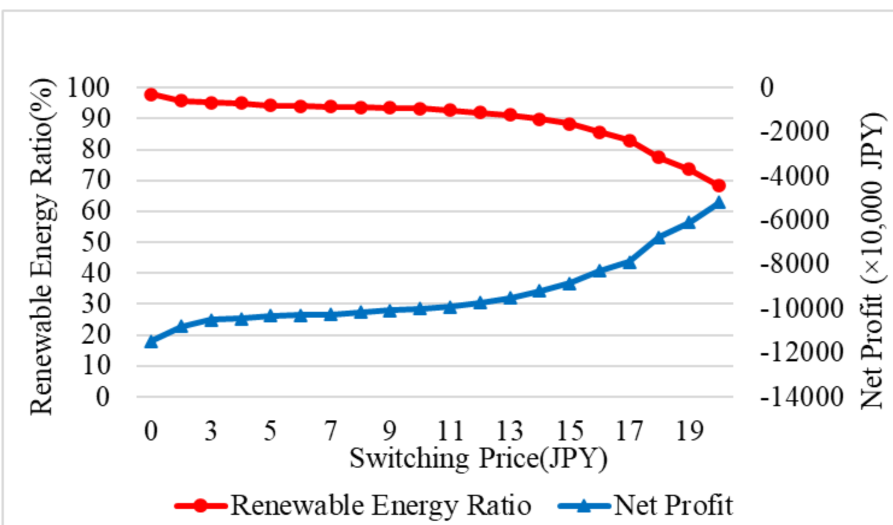

Fig 3: Relationship Between Switching Price, Renewable Energy Ratio, and Profit/Loss

Figure 3 summarizes these results and reveals two notable tendencies. First, setting the switching price slightly above zero (e.g., at 1 JPY/kWh) yields a marked improvement in profit.

This is because daytime market prices often drop to around 0.1 JPY/kWh when solar output is high, making market procurement temporarily more economical than buying from generators at fixed prices. Second, when the switching price exceeds roughly 16 JPY/kWh, profitability again increases sharply. This reflects the fact that the contracted prices—11 JPY/kWh for solar and 17 JPY/kWh for wind—become relatively attractive compared with elevated market prices. However, as the switching price increases and market procurement becomes more frequent, the system relies more heavily on market electricity, which tends to reduce the overall renewable energy ratio. Therefore, the switching price must be tuned carefully to balance economic performance and RE utilization.

Introduction of Battery Charging/Discharging Constraints

Table 2: Comparison of Battery Charging/Discharging Constraints (Unit: 10,000 JPY)

		Without Battery Operation Constraints	With Battery Operation Constraints	With Battery Operation Constraints (Switching Price = 1 JPY)
Cost	Generation Cost	17127	17127	16768
	Power Storage Cost	21703	2088	2088
	Interruptible Load Cost	1173	1173	1156
	Wheeling Cost	8891	8891	8891
	Electricity Purchase Cost	407	5765	5766
	Total Cost	49301	35044	34669
Revenue	Electricity Sales Revenue (Market)	4575	8616	8616
	Electricity Sales Revenue (Consumers)	33251	33251	33252
	Total Revenue	37826	41867	41868
Net Profit (Total Revenue − Total Cost)		-11475	6823	7199
Renewable Energy Ratio		98%	74%	72%

The previous results indicate that the high cost of battery charging and discharging is a major factor behind the negative profitability observed in the unconstrained battery case. To address this, we introduce an additional rule that compares the effective cost of battery operation with the prevailing market price and restricts charging/discharging to periods when it is economically advantageous.

Under this scheme, the model chooses between using the battery and trading with the market based on relative costs. Battery operations are allowed only when they clearly improve the objective value.

Table 2 compares three cases:

1. a VPP with batteries but without operation constraints,
2. a VPP with battery operation constraints, and
3. a VPP with battery operation constraints and a switching price of 1 JPY/kWh.

The results show that adding battery constraints alone substantially reduces storage costs and turns the previously negative profit into a positive one, while keeping a high RE ratio (around 74%). When the switching price of 1 JPY/kWh is combined with these constraints, profit further

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increases to approximately 72 million JPY per year, with a renewable energy ratio of 72%. This configuration offers a well-balanced compromise between environmental and economic objectives.

CONCLUSION

This study proposed and evaluated a business-oriented VPP model that explicitly considers the trade-off between renewable energy adoption and economic feasibility. Using an annual, hourly simulation for a VPP serving 2,000 households in the Kanto region of Japan, we obtained the following main findings:

1. **Clarification of the battery storage dilemma**
   The numerical results confirmed that intensive use of battery storage can raise the RE share to 98% but simultaneously causes a substantial operating loss (on the order of −115 million JPY). Under current cost assumptions, such a strategy is not economically sustainable for a VPP operator.
2. **Effectiveness of profit-driven operational rules**
   To resolve this issue, we introduced a switching price rule for choosing between market procurement and contracted generators, as well as constraints that limit battery usage to economically favorable periods. These rules proved highly effective in reducing storage costs and improving overall profitability. With both mechanisms applied and the switching price set to 1 JPY/kWh, the VPP achieved an annual profit of about 72 million JPY while maintaining a renewable energy ratio of 72%.
3. **Establishment of a balanced VPP business model**
   The results demonstrate that VPP implementation is not solely a technical challenge but also a matter of designing appropriate business rules. The proposed model provides a concrete operating strategy showing that VPPs can simultaneously support high levels of renewable energy penetration and maintain financial viability.

Future work will involve more detailed empirical validation, sensitivity analysis with respect to technology costs and market conditions, and extensions of the model to different regions and resource portfolios. These efforts are expected to contribute to the practical deployment of VPPs as a key component of sustainable energy systems.

ACKNOWLEDGEMENTS

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