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# Risk-Hedging Market Clearing for Flexible Ramping Products with Price-Maker Virtual Batteries

Weimin Wu†, Mingze Xu†, Yanting Huang†, and Shunbo Lei†

***Abstract*—Current Flexible Ramping Product (FRP) procurement relies heavily on gas-fired generators, which incur significant inefficiencies due to the "over-commitment" problem caused by minimum generation constraints. While HVAC-based Virtual Batteries (VBs) offer a flexible alternative, their large-scale aggregation transforms them from price-takers to price-makers, creating a unique financial risk: the HVAC load increasing phase may coincide with self-induced price spikes, eroding ramping revenues. To address this, this paper proposes a two-stage stochastic market clearing framework that co-optimizes energy and ramping services. We explicitly model the distinct "Up-Down" and "Down-Up" load shifting of VBs to provide ramping capacities. Crucially, a financial risk management mechanism is integrated into the optimization to hedge against the price volatility caused by the VBs' own load-shifting behavior. Numerical results demonstrate that the proposed method effectively mitigates the rigid commitment of gas units and ensures the economic viability of VB participation by shielding them from adverse price impacts.**

***Index Terms*—Flexible ramping product, virtual battery, price-maker, risk hedging, stochastic optimization.**

## I. Introduction

The increasing penetration of renewable energy sources has introduced significant uncertainty and variability to power system operations, leading to steep fluctuations in net demand. To manage these challenges and ensure operational flexibility and reliability, independent system operators (ISOs), e.g., the California ISO (CAISO), have integrated Flexible Ramping Products (FRPs) into their market structures [1]. These products are designed to reserve sufficient ramping capability to accommodate net load forecast errors and variability between scheduling intervals.

Traditionally, ramping requirements are predominantly met by gas-fired generators. However, this reliance exposes the system to significant inefficiencies. First, traditional generators are often located far from load centers, incurring high transmission congestion costs. Second, and more critically, gas generators suffer from the "over-commitment" problem. To address short-term demand spikes, operators must commit additional units. Due to minimum generation limits ($P_{\min}$) and minimum runtime constraints, these units cannot shut down immediately after the spike subsides. This inflexibility often forces the system to curtail renewable generation or leads to negative electricity prices during subsequent low-load periods [2].

In contrast, demand-side resources offer a cost-effective alternative. However, CAISO's 2022 analysis emphasized that eligible resources must be continuously dispatchable, a stringent requirement that restricts resources limited by activation frequency and slow response speeds [1]. Conversely, commercial HVAC systems, leveraging their building thermal inertia, can function as Virtual Batteries (VBs) without these limitations [3]. As illustrated in Fig. 1, HVAC-based VBs can provide flexibility through two distinct modes while maintaining energy neutrality (i.e., the net energy change over a cycle is zero to ensure efficiency and comfort): Up-Down capacity (UDC), which increases load to absorb excess power before decreasing it; and Down-Up capacity (DUC), which decreases load before recovering [3], [4]. By shifting loads, VBs effectively smooth the net load trajectory, mitigating the need for generator commitment and avoiding the associated $P_{\min}$ issues.

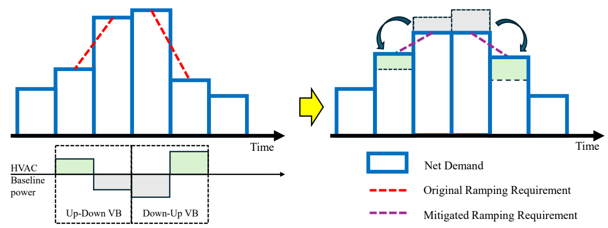


Fig. 1: Schematic of HVAC-based Virtual Batteries providing ramping services. (By providing Up-Down and Down-Up capacities, VBs smooth the net load curve, transforming the original ramping requirement into a mitigated trajectory.)

However, the integration of VBs into the ramping market introduces new economic risks. While the physical dispatch is feasible, the financial settlement is complex because VBs essentially modulate energy consumption. When aggregated at scale, HVAC-based VBs have the potential to become *price-makers*. The collective load shifting behavior can alter the real-time marginal prices, creating financial risks. For example, the "rebound" effect (energy recovery) might coincide with price spikes induced or exacerbated by the VBs' own actions. Consequently, the increased energy procurement costs could overshadow the revenue earned from providing ramping capacity, disincentivizing user participation. To address these challenges, this paper proposes a comprehensive market framework and a financial risk management mechanism. The main contributions are summarized as follows:

1) We propose a market architecture that incorporates HVAC-based VBs into the ramping capacity clearing process. This model explicitly accounts for the physical constraints of VBs, enabling them to replace expensive gas generators in managing net demand variability.
2) We develop a financial risk hedging mechanism embedded within the settlement process. By deriving a dynamic protection price, this method technically decouples VB revenue from self-induced price spikes, effectively immunizing price-maker participants against the "rebound effect" risks, etc.

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3) We demonstrate the incentive compatibility and scalability of the proposed framework through quantitative analysis. Case studies reveal a high-leverage subsidy effect, whereby a marginal concession in system surplus yields a disproportionate increase in user benefits. This demonstrates the mechanism's ability to foster a virtuous cycle, encouraging large-scale VB participation without compromising system economic efficiency.

## II. Mathematical Formulation

### A. Ramping Product Market Clearing with Virtual Batteries

Consider a power grid including a set of gas generators $\mathcal{G}$ and a set of aggregated HVAC-based virtual batteries (VBs) $\mathcal{V}$ over a scheduling horizon $\mathcal{T}$. The uncertainty of renewable generation and load is captured by a set of scenarios $\mathcal{S}$. The proposed two-stage stochastic model aims to co-optimize energy and ramping products as follows:

$$\min \quad F = \underbrace{\sum_{t\in\mathcal{T}} \Bigg[ \sum_{i\in\mathcal{G}} \Big( C_i^{\text{st}} v_{i,t} + C_i^{\text{sh}} w_{i,t} + C_i^{\text{cap}} (R_{i,t}^{\text{up}} + R_{i,t}^{\text{dn}}) \Big)}_{\text{Stage I: Generator Commitment \& Ramping Capacity}}$$
$$+ \underbrace{\sum_{j\in\mathcal{V}} \Big( C_j^{\text{cap,ud}} K_{j,t}^{\text{ud}} + C_j^{\text{cap,du}} K_{j,t}^{\text{du}} \Big) \Bigg]}_{\text{Stage I: VB Ramping Capacity Reservation}}$$
$$+ \underbrace{\sum_{s\in\mathcal{S}} \pi_s \sum_{t\in\mathcal{T}} \sum_{i\in\mathcal{G}} C_i^{\text{fuel}}(p_{i,t,s})}_{\text{Stage II: Expected Operating Cost}} \tag{1}$$

s.t.

$$u_{i,t} - u_{i,t-1} = v_{i,t} - w_{i,t}, \quad \forall i \in \mathcal{G}, t \in \mathcal{T} \tag{2a}$$
$$v_{i,t} + w_{i,t} \le 1, \quad \forall i \in \mathcal{G}, t \in \mathcal{T} \tag{2b}$$
$$0 \le R_{i,t}^{\text{up}} \le R_i^{\max} u_{i,t}, \ \ \forall i \in \mathcal{G}, t \in \mathcal{T} \tag{2c}$$
$$0 \le R_{i,t}^{\text{dn}} \le R_i^{\max} u_{i,t}, \ \ \forall i \in \mathcal{G}, t \in \mathcal{T} \tag{2d}$$
$$p_{i,t,s} = p_{i,t}^{\text{base}} + r_{i,t,s}^{\text{up,use}} - r_{i,t,s}^{\text{dn,use}}, \quad \forall i \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S} \tag{2e}$$
$$0 \le r_{i,t,s}^{\text{up,use}} \le R_{i,t}^{\text{up}}, \ \ \forall i \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S} \tag{2f}$$
$$0 \le r_{i,t,s}^{\text{dn,use}} \le R_{i,t}^{\text{dn}}, \ \ \forall i \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S} \tag{2g}$$
$$P_i^{\min} u_{i,t} \le p_{i,t,s} \le P_i^{\max} u_{i,t}, \quad \forall i \in \mathcal{G}, t \in \mathcal{T}, s \in \mathcal{S} \tag{2h}$$
$$\Delta x_{j,t,s} = x_{j,t,s}^{\text{ud}} - x_{j,t,s}^{\text{du}}, \quad \forall j \in \mathcal{V}, t \in \mathcal{T}, s \in \mathcal{S} \tag{2i}$$
$$0 \le x_{j,t,s}^{\text{ud}} \le K_{j,t}^{\text{ud}}, \ \ \forall j \in \mathcal{V}, t \in \mathcal{T}, s \in \mathcal{S} \tag{2j}$$
$$0 \le x_{j,t,s}^{\text{du}} \le K_{j,t}^{\text{du}}, \ \ \forall j \in \mathcal{V}, t \in \mathcal{T}, s \in \mathcal{S} \tag{2k}$$
$$K_{j,t}^{\text{ud}} \le K_j^{\max}, \ \ K_{j,t}^{\text{du}} \le K_j^{\max}, \quad \forall j \in \mathcal{V}, t \in \mathcal{T} \tag{2l}$$
$$L_{j,t,s}^{\text{H}} = L_{j,t}^{\text{base}} + \Delta x_{j,t,s} - \Delta x_{j,t-1,s}, \forall j \in \mathcal{V}, t \in \mathcal{T}, s \in \mathcal{S} \tag{2m}$$
$$\sum_{i\in\mathcal{G}} p_{i,t,s} = D_{t,s} + \sum_{j\in\mathcal{V}} L_{j,t,s}^{\text{H}} : \lambda_{t,s}, \quad \forall t \in \mathcal{T}, s \in \mathcal{S} \tag{2n}$$

The objective function (1) minimizes the total system cost by balancing investment decisions against expected operational outcomes. It comprises two distinct stages. The first stage represents the "here-and-now" decisions made prior to uncertainty realization. This includes the unit commitment costs (start-up $C^{\text{st}}$, shut-down $C^{\text{sh}}$) and the procurement of ramping capacity from both gas generators ($R^{\text{up/dn}}$) and virtual batteries. Specifically, VB capacity is categorized into Up-Down capacity ($K^{\text{ud}}$), facilitating load increase followed by a decrease, and Down-Up capacity ($K^{\text{du}}$), facilitating load decrease followed by an increase. The second stage represents the "wait-and-see" expected operating cost, calculated as the probability-weighted sum of fuel costs $C^{\text{fuel}}$ across all scenarios $\mathcal{S}$, where $\pi_s$ denotes the probability of scenario $s$.

Constraints (2a)-(2d) govern the first-stage commitment and capacity reservation for gas generators. Here, $u_{i,t}$, $v_{i,t}$, and $w_{i,t}$ are binary variables representing the commitment status, start-up, and shut-down actions, respectively. The procured ramping capacities $R_{i,t}^{\text{up}}$ and $R_{i,t}^{\text{dn}}$ are bounded by the maximum ramping rate $R_i^{\max}$ and the unit's status. In the second stage, (2e)-(2g) ensure that the actual power output $p_{i,t,s}$, defined as the base schedule $p_{i,t}^{\text{base}}$ adjusted by deployed flexibility $r_{i,t,s}^{\text{up/dn,use}}$, is strictly limited by the capacity purchased in the first stage. Additionally, constraint (2h) enforces the physical operating boundaries of the generators, ensuring that the realized power output remains within the minimum ($P_i^{\min}$) and maximum ($P_i^{\max}$) limits whenever the unit is committed.

For virtual batteries, the operational flexibility is modeled through (2i)-(2m). We define two distinct deployment variables: $x_{j,t,s}^{\text{ud}}$ represents the deployment of Up-Down capacity, while $x_{j,t,s}^{\text{du}}$ represents the deployment of Down-Up capacity. Constraints (2j)-(2k) enforce that the real-time usage of each service type does not exceed its respective reserved capacity ($K^{\text{ud}}, K^{\text{du}}$), which is bounded by the maximum capacity $K_j^{\max}$ in (2l). The net power deviation $\Delta x_{j,t,s}$ is then incorporated into the load dynamics in (2m).

Crucially, the difference-based formulation in (2m) (i.e., $\Delta x_{j,t,s} - \Delta x_{j,t-1,s}$) inherently enforces energy neutrality over the scheduling horizon. Since $x$ is also associated with HVAC state deviations (e.g., temperature) that must eventually be restored, the integral of these load changes sums to zero (assuming boundary conditions $\Delta x_0 = \Delta x_T = 0$). This guarantees that VBs provide pure power flexibility without acting as net energy consumers, thereby also preserving the long-term thermal comfort of end-users while capturing the rebound effect, etc. Finally, (2n) ensures power balance in each scenario, matching total generation to the inelastic demand $D_{t,s}$ and VB load. The dual variable associated with this constraint, $\lambda_{t,s}$, represents the energy marginal price.

### B. Risk Management via Protection Price Mechanism

While VBs provide essential flexibility, their aggregated load shifting behavior can significantly alter the load profile $D_{t,s} + \sum L_{j,t,s}^{\text{H}}$, making them price-makers. The resulting change in spot prices $\lambda_{t,s}$, combined with the rebound effect, etc., may inadvertently increase the energy procurement costs for VB users. To mitigate this risk, we introduce a financial risk management mechanism.

First, we define a *Baseline Model* representing the system operation without VB participation, obtained by excluding VB terms from (1):

$$F^{\text{ref}} = \min \quad \sum_{t\in\mathcal{T}} \sum_{i\in\mathcal{G}} \Big( C_i^{\text{st}} v_{i,t} + C_i^{\text{sh}} w_{i,t} + C_i^{\text{cap}} (R_{i,t}^{\text{up}} + R_{i,t}^{\text{dn}}) \Big)$$

$$+\sum_{s\in\mathcal{S}}\pi_s\sum_{t\in\mathcal{T}}\sum_{i\in\mathcal{G}}C_i^{\text{fuel}}(p_{i,t,s}^{\text{ref}}) \tag{3}$$

subject to the baseline power balance with shadow prices $\lambda_{t,s}^{\text{ref}}$.

Let $F^*$ and $\lambda_{t,s}$ denote the optimal cost and energy prices from the proposed model. We introduce a protection price $\rho_t$ to cap the settlement price during energy charging periods. We model the problem as a Cooperative Surplus Sharing Game. The goal is to determine $\rho_t$ such that the total economic surplus created by VBs is fairly distributed between the System Operator (ISO) and VBs.

We define the Net Surplus for both parties and present the clearing model as follows:

*1) System Operator Net Surplus ($\Delta S_{\text{sys}}$):* The system operator benefits from the reduction in operating costs ($F^{\text{ref}}-F^*$), but loses revenue due to the price protection subsidy provided to VBs:

$$\Delta S_{\text{sys}} = (F^{\text{ref}}-F^*) - \underbrace{\sum_{s\in\mathcal{S}}\pi_s\sum_{t\in\mathcal{T}}\sum_{j\in\mathcal{V}}(\lambda_{t,s}-\hat{\lambda}_{t,s})L_{j,t,s}^{\text{H}}}_{\text{Subsidy Cost}} \tag{4}$$

where $\hat{\lambda}_{t,s}=\min(\lambda_{t,s},\rho_t)$ is the effective settlement price.

*2) VBs Net Surplus ($\Delta S_{\text{VBs}}$):* The VB providers benefit from the reduction in energy payments compared to the baseline, plus the capacity revenue earned in the ramping market:

$$\Delta S_{\text{VBs}} = (\mathbb{E}[E^{\text{ref}}]-\mathbb{E}[E^{\text{prot}}]) + R^{\text{cap}} \tag{5}$$

Here, $\mathbb{E}[E^{\text{ref}}]=\sum_{s,t,j}\pi_s\lambda_{t,s}^{\text{ref}}L_{j,t}^{\text{base}}$ is the baseline energy cost, and $\mathbb{E}[E^{\text{prot}}]=\sum_{s,t,j}\pi_s\hat{\lambda}_{t,s}L_{j,t,s}^{\text{H}}$ is the protected energy cost. $R^{\text{cap}}$ is the total ramping capacity revenue.

*3) Clearing Model:* To achieve a fair equilibrium, the protection price $\rho_t$ is optimized to minimize the disparity between the system operator's and VBs' surpluses:

$$\min_{\rho_t\geq 0,\delta\geq 0} \quad \delta \tag{6}$$

subject to the fairness constraint:

$$-\delta \leq \Delta S_{\text{sys}} - \Delta S_{\text{VBs}} \leq \delta \tag{7}$$

and the linearization constraints for $\hat{\lambda}_{t,s}$:

$$\hat{\lambda}_{t,s} \leq \lambda_{t,s} \tag{8a}$$

$$\hat{\lambda}_{t,s} \leq \rho_t \tag{8b}$$

$$\hat{\lambda}_{t,s} \geq \lambda_{t,s} - M(1-z_{t,s}) \tag{8c}$$

$$\hat{\lambda}_{t,s} \geq \rho_t - Mz_{t,s} \tag{8d}$$

where $z_{t,s}\in\{0,1\}$ identifies active constraint regions. This formulation ensures that $\rho_t$ settles at a value where the financial benefits are shared equally ($\Delta S_{\text{sys}}\approx\Delta S_{\text{user}}$), preventing both trivial zero prices and excessive prices that negate incentives.

## III. Case Study

### A. Simulation Setup

The proposed method is validated on a test system comprising three gas generators and two aggregated virtual battery (VB) units. The operational cost of gas generators is represented by a quadratic fuel cost function, which captures the non-linear relationship between power output and fuel consumption (i.e., the heat rate curve). The coefficients, along with other techno-economic parameters for the generators and VBs, are detailed in Table I.

TABLE I: Generator and Virtual Battery Parameters

| **Generator Parameters** | **Unit Index** | | |
|---|---|---|---|
| | ***G1*** | ***G2*** | ***G3*** |
| Fuel Coeff. $a$ (\$/MW$^2$) | 0.15 | 0.25 | 0.12 |
| Fuel Coeff. $b$ (\$/MW) | 25 | 30 | 28 |
| Fuel Coeff. $c$ (\$) | 100 | 120 | 110 |
| Start-up Cost (\$) | 500 | 600 | 550 |
| Shut-down Cost (\$) | 300 | 350 | 320 |
| Ramping Cost (\$/MW) | 150 | 160 | 155 |
| Min Output $P^{\min}$ (MW) | 20 | 30 | 25 |
| Max Output $P^{\max}$ (MW) | 150 | 200 | 180 |
| Ramping Rate $R^{\max}$ (MW) | 40 | 50 | 45 |
| **Virtual Battery (Aggregated) Parameters** | **Unit Index** | | |
| | ***VB1*** | ***VB2*** | **–** |
| Max Capacity $K^{\max}$ (MW) | 50 | 40 | – |
| $C^{\text{cap,ud}}$ (\$/MW) | 2.5 | 3.5 | – |
| $C^{\text{cap,du}}$ (\$/MW) | 2.5 | 3.5 | – |

* $a$, $b$, and $c$ denote the quadratic, linear, and no-load cost coefficients.

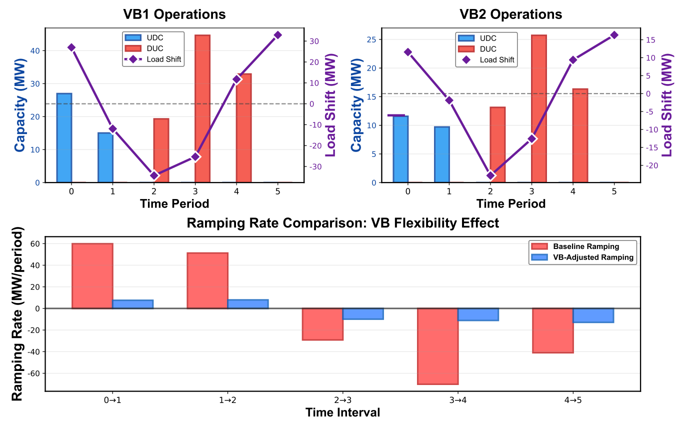


Fig. 2: Optimal dispatch of aggregated virtual batteries, and ramping requirement mitigation.

### B. Performance Analysis

*1) Operational Feasibility and Price-Maker Impact Analysis:* Fig. 2 illustrates the optimal dispatch results. The upper panels depict the utilization of Up-Down capacities (UDC) and Down-Up capacities (DUC) by the VBs. It is observed that VBs dynamically shift their load profiles (indicated by purple lines) to accommodate system needs. Crucially, the energy neutrality constraint is strictly enforced over the scheduling horizon, ensuring that the integral of load adjustments sums to zero, thereby maintaining VB efficiency.

The bottom panel of Fig. 2 demonstrates the tangible benefit of this flexibility. The introduction of VBs significantly smooths the net load profile, leading to a drastic reduction in the ramping requirements (blue bars) compared to the baseline (red bars). This confirms that, from a physical standpoint, aggregated VBs are a viable and highly effective alternative to gas-fired generators for providing ramping services.

While physically effective, the massive integration of VBs introduces complex market dynamics, as shown in Fig. 3. A comparison of the spot price distributions reveals a significant "price-maker" effect. The distribution with VBs (green violins) generally shifts upward compared to the baseline scenario

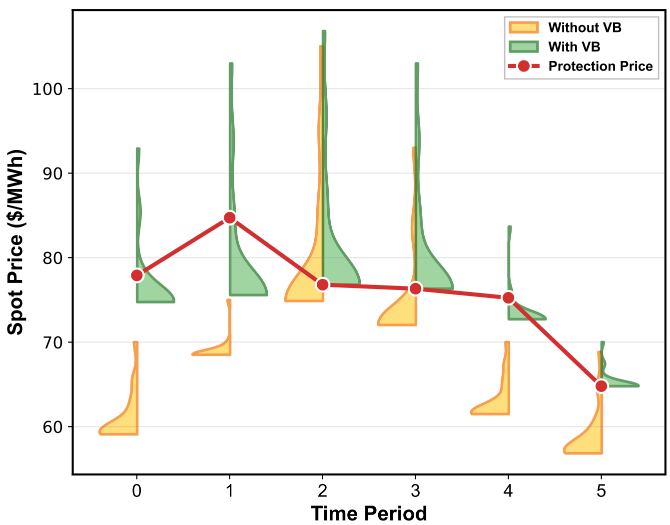


Fig. 3: Spot price distribution comparison, and protection price variation.

TABLE II: Economic Analysis Results under Different VB Supply Scenarios

| —— | VB Capacity Cases | | |
|---|---|---|---|
| | ***Insufficient*** | ***Adequate*** | ***Excessive*** |
| VB Capacity (MW) | $K_1^{\max}=50$ $K_2^{\max}=30$ | $K_1^{\max}=50$ $K_2^{\max}=40$ | $K_1^{\max}=70$ $K_2^{\max}=60$ |
| *Baseline (No VBs): System Cost = $220,656* | | | |
| **Mechanism I** | **Without Protection Price** | | |
| System Cost ($) | 218,741 | 215,313 | 201,838 |
| Saving vs Base (%) | 0.87% | 2.42% | 8.53% |
| VB Benefit ($) | 3,656 | 4,619 | 7,646 |
| **Mechanism II** | **With Protection Price** | | |
| Gen. Cost ($) | 218,741 | 215,313 | 201,838 |
| Subsidy Payment ($) | 0 | 363 | 5,586 |
| Total Sys. Cost ($) | 218,741 | 215,675 | 207,424 |
| Saving vs Base (%) | 0.87% | 2.26% | 6.00% |
| VB Benefit ($) | 3,656 | 4,981 | 13,232 |
| Benefit Improv. (%)[a] | 0% | **+7.8%** | **+73.1%** |
| Subsidy Ratio (%)[b] | 0% | **7.3%** | **42.2%** |

[a] Calculated as $(\text{Benefit}_{\text{Mech. II}} - \text{Benefit}_{\text{Mech. I}})/\text{Benefit}_{\text{Mech. I}}$.
[b] Calculated as $\text{Subsidy\_Payment}/\text{VB\_Benefit}_{\text{Mech. II}}$.

where ramping products are provided solely by generators (orange violins). This phenomenon validates the concern raised earlier: the load-shifting behavior of HVAC-based VBs to provide ramping services tends to coincide with or exacerbate high-price periods, exposing VBs to the risk of increased energy costs, potentially eroding their ramping revenues.

However, the proposed protection price mechanism effectively mitigates this financial risk. As plotted by the red line in Fig. 3, the protection price dynamically adjusts but consistently remains in the lower quantile of the realized spot price distribution (green areas). Since the settlement is based on $\min(\text{Spot Price}, \text{Protection Price})$, the positioning of the protection price below the bulk of the high spot prices indicates that the system is actively protecting VB participants. By capping the settlement price, the mechanism allows VBs to pay the lower protection price instead of the high spot price. This direct subsidy reduces their energy costs, ensuring they remain profitable even when market energy prices spike.

*2) Economic Efficiency and Incentive Compatibility:* Table II presents a comparative economic analysis across three VB capacity scenarios to evaluate the scalability of the proposed mechanism. In the "Insufficient" scenario, where flexibility resources are scarce, the system savings are marginal (0.87%), leaving little fiscal room for subsidies. However, due to the high market value of these scarce resources, VBs naturally secure sufficient returns without intervention, resulting in a 0% subsidy ratio and identical outcomes for both mechanisms.

As VB participation expands to the "Excessive" scenario, the dynamics shift significantly. The massive integration of VBs drives the system cost down drastically, creating a substantial efficiency surplus (8.53% potential saving). This surplus enables the system to adopt a more generous stance. By reallocating a portion of these savings as subsidies ($5,586), the system accepts a slightly lower total saving (6.00%) compared to the case with Mechanism I, but in exchange, it triggers a disproportionate surge in incentives for VBs. Specifically, this strategic subsidy boosts the VBs' benefit by 73.1% (from $7,646 to $13,232), demonstrating a high leverage effect where a moderate system concession yields massive gains of VBs.

This result underscores the cooperative nature of the proposed framework. While the protection price mechanism seemingly reduces the system's maximum theoretical saving, it establishes a "win-win" equilibrium. For the system, it secures a stable cost reduction compared with the baseline; for VBs, it provides a robust safety net that guarantees profitability even when market prices are variable. Consequently, this risk management strategy effectively mitigates the "price-maker" risk, fostering a virtuous cycle that encourages continuous VB capacity expansion and long-term market sustainability.

## IV. Conclusion

This paper proposes a risk-hedging market clearing framework that integrates HVAC-based Virtual Batteries (VBs) to provide flexible ramping products. By explicitly modeling the price-maker characteristic of aggregated VBs and introducing a protection price mechanism, the proposed approach effectively mitigates the over-commitment of gas generators while shielding VB participants from self-induced price volatility. Numerical results confirm that the mechanism achieves a win-win outcome, securing system cost savings while significantly boosting VB benefits. Future work will focus on two main directions: first, incorporating power flow constraints to evaluate the impact of network congestion on VB dispatch and locational marginal pricing; and second, enhancing the economic model by endogenizing VB capacity costs, transitioning from fixed parameters to dynamic representations that reflect real-time opportunity costs and bidding behaviors.

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# I. Review #15A

## A. Paper summary

The paper studies incorporating virtual batteries consisting of HVAC into grid optimization.

## B. Comments for authors

With recent regulatory changes such as FERC Order 2222, incorporating DER aggregation into market clearing and system dispatch is an important question. The HVAC model considered in this study is too simplified, and the most important characteristic of HVAC is its dependence on human thermal comfort preference and behavior, which is absent from this study. A recent study shows human preference and thermal override are critical factors in the scalability and reliability of HVAC-based demand response solutions. Hence, the paper can be strengthened by at least considering a thermal deviation penalty in the cost function/bid curve design.

## C. Summarize your recommendation in one to two sentences

The paper can be strengthened to consider human thermal comfort and/or possible control override in HVAC cost and reliability.

— *Anonymous reviewer*

# II. Review #15B

## A. Paper summary

This note is concerned with the problem of coordinating HVAC–based virtual batteries (VBs) such that they can participate in demand response without becoming price makers. This is a highly relevant problem as if the VBs become price makers then by definition they influence prices which can lead to increased risk which results in higher prices – the problem they are intended to mitigate. The authors propose a "two stage" model ad well as a risk hedging price protection mechanism that caps settlement prices during charging periods. Numerical experiments demonstrate that the approach has a lot of potential.

## B. Comments for authors

I believe that the problem is interesting and of significant interest to the Power Up audience. The note is also clearly written and manages to pack a lot into four pages.

Strengths:

- Solid problem formulation addressing a real issue: Integrating demand-side flexibility—specifically HVAC-based virtual batteries (VBs)—into flexible ramping product (FRP) markets, which are currently dominated by gas generators and suffer from inefficiencies such as minimum generation constraints and over-commitment.
- The framing of aggregated VBs as potential price-makers is a nice conceptual contribution, since (to my knowledge) most prior work treats demand-side resources as price-takers.
- The framework is comprehensive in that it connects physical flexibility modeling (Up-Down and Down-Up load shifting) with market settlement design.
- The proposed protection price mechanism attempts to address the financial risk that arises when VBs affect the prices they are exposed to.

Weaknesses:

- The optimization problem are presented in a manner which is slightly confusing in terms of both presentation and terminology:
  i) The note refers to a two-stage stochastic model, but in power market literature the phrase "two-stage" can easily be confused with bi-level or equilibrium models (e.g., market clearing vs. participant optimization). Here the formulation is a standard stochastic unit commitment structure (first-stage commitment/reservation, second-stage dispatch) rather than a market equilibrium or strategic bidding model. Since the paper simultaneously emphasizes price-maker behavior, readers may expect a bi-level or MPEC formulation, which is not actually present.
  ii) The mathematical formulation omits several elements necessary for clarity, e.g., the decision variables are not explicitly defined - it takes a lot of effort to work out what is a variable and what is a parameter. The domains of variables (binary, continuous) are inconsistently stated. Together this makes it difficult to determine if the problem is tractable (convex - if so LP, SOCP, SDP?) or non-convex - in which case what is meant be a solution- local or global?
- The protection price mechanism lacks strong theoretical justification. It's framed as a surplus-sharing rule, but several questions remain unclear: Why is equal surplus sharing the appropriate fairness criterion? Is the protection price guaranteed to exist and be unique? Does the mechanism preserve market efficiency or incentive compatibility in more realistic settings?

### C. Summarize your recommendation in one to two sentences

I think the paper offers enough novelty and demonstrates potential of the method. In places the paper can be strengthened by improving the technical presentation and providing methodological justification but the content is solid.

*— James Anderson*

## III. Review #15C

### A. Paper summary

In this paper, the authors propose a stochastic market clearing framework to co-optimize energy and ramping services of conventional generators and virtual batteries (aggregations of HVACs) together. Virtual batteries are capable of providing up-down and down-up load shifting capacity. To prevent virtual batteries from creating self-induced price spikes during load shifting, which could discourage participation in flexible ramping markets, the authors introduce a protection price mechanism. This protection price is determined relative to the baseline case with no virtual battery participation where the surplus (i.e., cost savings from using virtual batteries to provide flexible ramping instead of generators) is split between the system operator and the virtual batteries. This is formulated as a stochastic problem that considers different scenarios of uncertain and uncontrollable net load, $D_{t,s}$.

### B. Comments for authors

- I find this to be an interesting and relevant problem, particularly regarding the financial settlement and incentive design for virtual batteries providing load shifting services.
- I'm aware that load shifting with HVAC can cause additional energy consumed (i.e., the load shifting process may not be energy neutral when providing up-down or down-up capacity). How would this affect the market-clearing framework if the service is not truly energy neutral?
- In the formulation, the capacity of the virtual battery is decoupled from the physical model of the aggregated HVAC systems. Could you provide additional details or references on how $K_j^{\max}$ would be calculated? The note would be strengthened by a brief discussion/acknowledgement of how the available flexibility depends on underlying HVAC dynamics and user behavior.
- How many uncertainty scenarios are included in the stochastic case study?
- Minor notation issues or typos:
  - contribution 3 on page 1 "We the incentive compatibility…",
  - equation (2k) is $K_{j,t}$ is missing superscript "du"
  - You are missing the sets you are summing over in equation (3) (i.e., $\mathcal{T}$, $\mathcal{G}$, and $\mathcal{S}$)

### C. Summarize your recommendation in one to two sentences

I think this paper presents an interesting contribution and fits well as a technical note. The proposed framework is clear and relevant, with only minor clarifications needed.

*— Anna Stuhlmacher*

## IV. Brief response to reviewers (optional)

We sincerely thank all reviewers for their constructive comments and positive feedback. We have revised the final version by correcting typos, improving notation consistency, and fixing the specific issues identified by the reviewers, including the missing verb, the notation error in the VB formulation, and the missing summation sets in the objective function.

Due to the strict page limit of this technical note, we could not fully expand the discussions on HVAC comfort modeling, user behavior, energy neutrality, and theoretical justification. These important suggestions are being incorporated into an extended version of this work, and we look forward to discussing them at the conference.

## V. Brief summary of changes made to the final paper

In the final version, we corrected typographical and notation errors, improved the consistency of the mathematical formulation, and addressed the specific minor issues pointed out by the reviewers. We also de-anonymized the paper by adding author names, affiliations, and funding acknowledgement.