PRICING AND REMUNERATING LOAD SHIFTING FLEXIBILITY IN ELECTRICITY MARKETS

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Abstract

Under recent trends of increasing renewable generation incorporation, flexibility has become a scarce asset to power grids, and thus loads and technologies with flexibility see huge economic opportunities. However, current energy-only markets are not well-designed to capture (and thus remunerate) flexibility from manufacturing and storage technologies, often leading to price volatility in space and time. A recently developed market design proposes the concept of virtual link to capture load/power-shifting flexibility from flexible loads such as modular manufacturing plants with a simple high-level abstraction. We demonstrate that this new market design prices/remunerates flexibility via price volatility in space and time, and the new market design satisfies basic market properties. We also show how the market design can be extended to capture more complicated flexibility providers like storage systems and how the market model reveals interesting effects arising from their participation, such as effects of physical parameters (e.g. efficiency) and benefits of decentralization.

Keywords

Electricity Markets, Flexibility, Manufacturing, Battery, Pricing.

Introduction

The power grid is undergoing major structural changes due to increasing adoption of renewable power, with multiple U.S. states setting ambitious renewable portfolio standards that dictate the required level of renewable energy use in the near future (e.g. California: 100% by 2045, Minnesota: 25% by 2025, New York: 70% by 2030) [2]. A critical challenge that emerges here is the unsteady, non-dispatchable, and spatio-temporal nature of renewable power. This leads to higher risk of real-time power imbalance throughout the power systems, which can be reflected by volatile electricity prices in space and time. Under the circumstances, flexibility has become a key asset in power system operations.

Traditionally, independent system operators (ISO) harness supply-side flexibility from dispatchable power plants (e.g. gas turbines) that can be quickly switched on or off (Babatunde et al., 2020). As the level of renewable energy rises, the energy community looks for new flexibility resources, especially from the demand side. For instance, several types of loads and technologies are identified as great sources of space-time shifting flexibility. Such loads include data centers (Wierman et al., 2014), modular manufacturing plants, and energy storage systems. In the context of manufacturing, there is an ongoing trend to deploy small-scale, modular production facilities as a way to harness distributed and stranded resources (e.g., waste streams, biomass, and renewable power) and to gain more flexibility in both investment and operations (Allman and Zhang, 2020; Baldea et al., 2017). The deployment of modular manufacturing systems would decentralize power loads and potentially aid power grid operations. A key example of this trend is that of ammonia and hydrogen manufacturing, which are currently produced at large centralized facilities (Smith et al., 2020). At the same time, it has been recently shown that space-time electricity market dynamics incentivize the deployment of modular systems and to decentralize loads; this is because exploiting space-time dynamics provides investors with a mechanism to mitigate risk (by exploiting price differences at across space and time (Shao and Zavala, 2019).

Modern electricity market takes a complex hierarchical structure that operates at multiple time scales (Dowling et al., 2017). In general, ISOs in the U.S. hold energy-only markets for electricity transactions, and ancillary markets for regulation and reserve ancillary services. An example schematic of the California ISO (CAISO) can be found in figure 1. As energy storage and flexible loads demonstrate great flexibility potential (Sioshansi et al., 2009; Tang et al., 2021), decisions have been made on the policy level to facilitate development of new market structures. In 2018, the Federal Energy Regulatory Commission (FERC) released Order 841 that aimed to remove barriers to wholesale electricity mar-

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[2] https://www.ncsl.org/research/energy/renewable-portfolio-standards.aspx

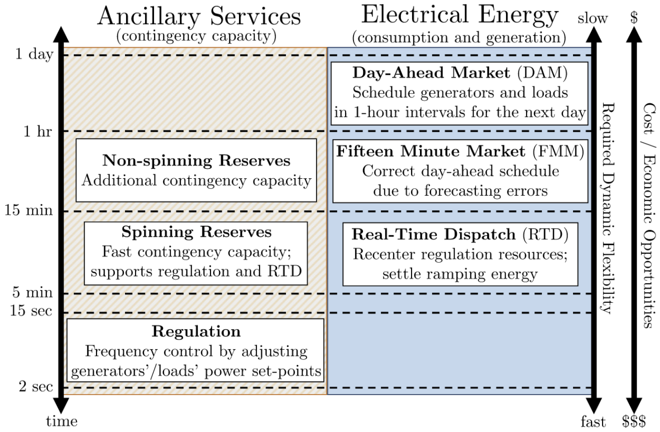


Figure 1: Multi-scale electricity market structure (Dowling et al., 2017).

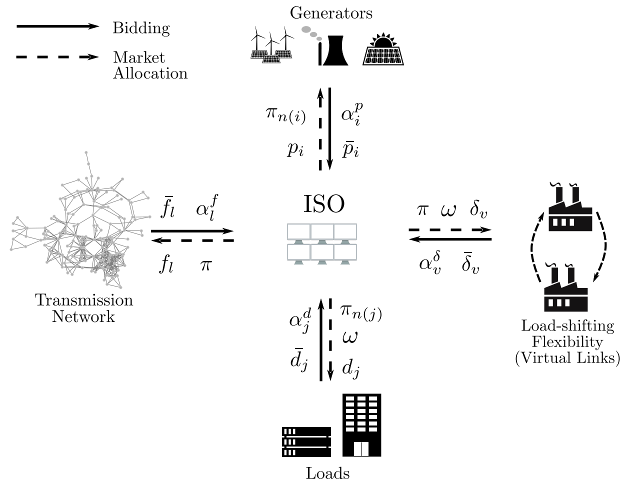


Figure 2: Market clearing procedure with virtual links. Bid price parameters are defined as αs, and bid quantity (capacity) parameters are defined with bars. π denotes the optimal prices, and p, d, f, δ denote optimal allocations.

ket participation of ESR systems. Much research in market design for flexibility focuses on flexibility provision in ancillary markets (Engels, 2020; Degefa et al., 2021), as the concept of flexibility is closely related to regulation and reserve services. However, participation of flexibility in energy-only markets is becoming more interesting recently because of access to more and cheaper renewable power, which prompts large loads like Google to trade in wholesale energy markets (Niccolai, 2010). Yet, work on generalized energy market designs for flexible loads/technologies is lacking. This motivates our recent work of market designs that capture shifting flexibility using the notion of virtual links.

Market Design with Virtual Links

We consider an electricity market running over a time period $\mathcal{T}$. The market is defined on a transmission network with nodes $\mathcal{N}$ and transmission lines $\mathcal{L}$. The market can be viewed as a space-time graph problem, with space time nodes $(n,t) \in \mathcal{N} \times \mathcal{T}$, where transmission lines are duplicated over time. Standard electricity markets include loads (consumers) indexed by $j \in \mathcal{D}$, generators (suppliers) indexed by $i \in \mathcal{S}$ and the transmission network (transmission service provider) indexed by $k \in \mathcal{K}$ as participants. Loads make payments to procure electricity, generators get remunerated from producing electricity, and transmission gets remunerated from its transmission services (moving electricity around in space).

In our proposed market design, we define virtual links as a set of new participants, serving as *flexibility providers*. A virtual link v is defined by a pair of sending and receiving space-time nodes: $\mathrm{snd}(v) := (n_{\mathrm{snd}(v)}, t_{\mathrm{snd}(v)}), \mathrm{rec}(v) := (n_{\mathrm{rec}(v)}, t_{\mathrm{rec}(v)})$, which mark the source and destination. The virtual link captures load or power shifting services, e.g. from modular manufacturing plants that can schedule their production level in space and time. This definition is general in that it can be used to capture electricity load shifting in pure space (e.g. shifting production from one site to another for a fixed time), in pure time (e.g. load delays in demand response programs), and in space and time.

Our proposed market clearing procedure for dispatchable loads across space and time using virtual links can be described as follows. The procedure is illustrated in figure 2.

1. Bidding: each participant makes a bid, consisting of a bid price and a bid quantity. The bid price means a threshold price to participate in the market. For instance, bid prices for loads mean the maximum unit price to purchase electricity, and bid prices for generators mean the minimum unit price to sell electricity. For virtual links, bid prices mean the minimum unit price for shifting loads or power. Similarly, a bid quantity means the maximum amount of electricity for participation. This means capacity for generators, transmission lines and virtual links.

2. Optimization: Once all the bid information is collected as parameters, the ISO solves an optimization problem to determine the optimal allocation of electricity (from the primal solution) and clearing prices (from the dual solution).

3. Execution: the transactions are executed based on the optimal solutions. Electricity allocations are executed based on the primal solution values, and pricing and remuneration for participants are made based on the dual solution values.

Now we state the market clearing problem. For simplicity, we first consider a setting where loads can be dispatched in space and time. We use virtual links to represent shifting of loads, not power. This model can be used as a simple energy-only market participation model for flexible load technologies such as modular manufacturing to offer flexibility. The market clearing problem is as follows (Zhang et al.,

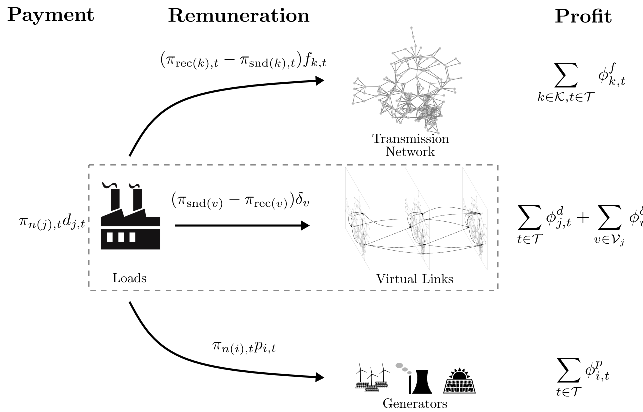


Figure 3: Payment, remuneration and profit for market participants.

2020).

$$
\begin{aligned}
\min_{d,p,f,\theta,\delta}\quad & \sum_{t\in\mathcal{T}}\Big(\sum_{i\in\mathcal{S}}\alpha^p_{i,t}p_{i,t}+\sum_{k\in\mathcal{K}}\alpha^f_{k,t}f_{k,t} \\
& \qquad -\sum_{j\in\mathcal{D}}\alpha^d_{j,t}d_{j,t}\Big)+\sum_{v\in\mathcal{V}}\alpha^\delta_v\delta_v \qquad (1a)\\
\text{s.t.}\quad & \sum_{k\in\mathcal{K}_n^{\mathrm{rec}}}f_{k,t}+\sum_{i\in\mathcal{S}_n}p_{i,t}+\sum_{v\in\mathcal{V}_{n,t}^{\mathrm{snd}}}\delta_v=\sum_{k\in\mathcal{K}_n^{\mathrm{snd}}}f_{k,t}\\
& \quad +\sum_{j\in\mathcal{D}_n}d_{j,t}+\sum_{v\in\mathcal{V}_{n,t}^{\mathrm{rec}}}\delta_v,\ (\pi_{n,t})\, n\in\mathcal{N},t\in\mathcal{T} \qquad (1b)\\
& f_{l^+,t}-f_{l^-,t}=B_l(\theta_{\mathrm{snd}(l),t}-\theta_{\mathrm{rec}(l),t}),\ l\in\mathcal{L},t\in\mathcal{T} \qquad (1c)\\
& 0\le\sum_{j\in\mathcal{D}_n}d_{j,t}+\sum_{v\in\mathcal{V}_{n,t}^{\mathrm{rec}}}\delta_v-\sum_{v\in\mathcal{V}_{n,t}^{\mathrm{snd}}}\delta_v\le\bar{d}^{\max}_{n,t},\\
& (\omega^l_{n,t},\omega^u_{n,t})\quad n\in\mathcal{N},t\in\mathcal{T} \qquad (1d)\\
& 0\le d\le\bar{d},0\le p\le\bar{p},0\le f\le\bar{f},0\le\delta\le\bar{\delta} \qquad (1e)
\end{aligned}
$$

Here the primal decision variables (d,p,f,δ) are power allocations to loads, generators, transmission lines and virtual links. The decision variables are indexed by participant and time. The objective function (1a) is to minimize the negative of the social surplus, which is the difference between total load utility and total cost of generation and services. Note that the social surplus depends on the bid prices. Equation (1b) captures the power balance at each space-time node. Equation (1c) captures Kirchhoff's law (linear approximation model) for power flows. Equation (1d) captures the capacity for actual amount of load at each space-time node, which arises from practical limits such as capacity of a plant. Equation (1e) are the capacity constraints for the allocations, which depend on bid capacity parameters. In modern ISOs, the optimal values of constraints (1b) are used as the clearing prices, which are referred to as locational marginal prices (LMP) in power systems community.

As a standard market analysis practice, one can form a partial Lagrangian by dualizing the power balance constraint (1b). This will allow us to show that the optimal solution for the market clearing problem also maximizes the profit for all market participants subject to optimal dual prices, where the profit functions are defined as follows:

$$\phi^d_{j,t}:=(\alpha^d_{j,t}-\hat{\pi}_{n(j),t})d_{j,t} \qquad (2a)$$

$$\phi^\delta_v:=(\hat{\pi}_{\mathrm{snd}(v)}-\hat{\pi}_{\mathrm{rec}(v)}-\alpha^\delta_v)\delta_v \qquad (2b)$$

$$\phi^p_{i,t}:=(\pi_{n(i),t}-\alpha^p_{i,t})p_{i,t} \qquad (2c)$$

$$\phi^f_{k,t}:=(\pi_{\mathrm{rec}(k),t}-\pi_{\mathrm{snd}(k),t}-\alpha^f_{k,t})f_{k,t} \qquad (2d)$$

where $\hat{\pi}_{n,t}:=\pi_{n,t}+\omega^u_{n,t}-\omega^l_{n,t}$. The payment and remuneration process is sketched in figure 3. Here are several key takeaways. First, the clearing prices determine the amount of money paid/received by each participant. Second, the virtual links are remunerated via price difference across the source and destination space-time nodes, similar to how transmission lines are remunerated in space. This shows how price volatility plays a key role in incentivizing flexibility. Third, virtual links allow flexible loads to bid in flexibility into the market, which is generating an additional stream of revenue for them.

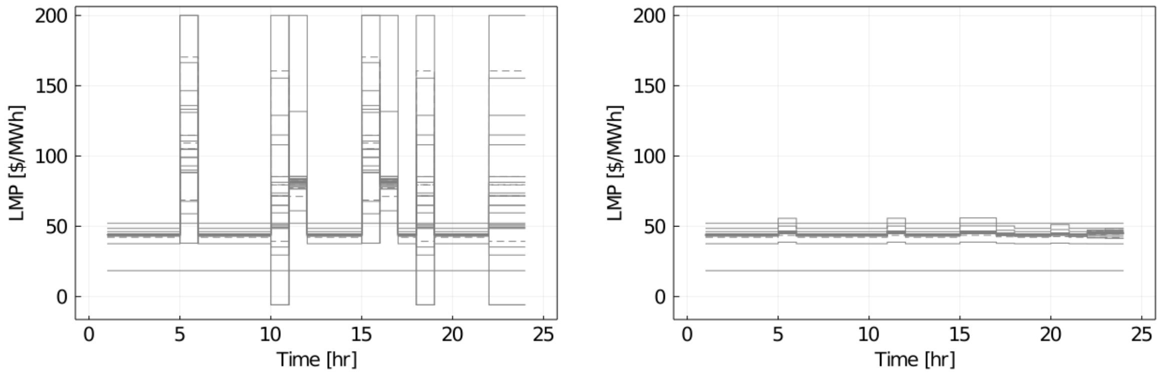
Market and Pricing Properties

In this section we briefly review some important market and pricing properties of the proposed market design. This section is based on work by Zhang and Zavala (2021). A well-designed market clearing formulation must satisfy the following economic properties:

- *Competitive Equilibrium:* The clearing formulation must deliver allocations and prices that represent a competitive equilibrium. That means the market must deliver allocations that balance supply and demand and that maximize the collective profit for all players. This property also ensures that the ISO does not interfere with the competitive nature of the market players.
- *Revenue Adequacy:* The clearing formulation delivers allocations and prices such that the total amount of money paid by service requesters (consumers) covers the total amount paid to all service providers (suppliers and transmission). This also ensures that the ISO does not have financial gain.
- *Cost Recovery:* The clearing formulation delivers allocations and prices such that no cleared player incurs a financial loss (it recovers its operating cost).

As mentioned in the last section, the optimal solution of (1) also solves the profit maximization problem for each participant. This means it satisfies competitive equilibrium, as no participant will be incentivized to move away from the primal solution given the dual (price) solution. The solution also satisfies cost recovery, as no participation is always a feasible solution for participants (which corresponds to zero profit). Revenue adequacy is also satisfied as visualized in figure 3; in fact, we can show the total payment is exactly equal to the sum of all remuneration streams.

In terms of pricing properties, we establish how participation of virtual links affects the price behavior of the market as a whole. Informally, the key results can be summarized as follows:



(a) No virtual links

(b) With virtual links

Figure 4: Price trajectories of 30-bus case study (Zhang and Zavala, 2021). Dashed lines denote nodes with flexible loads.

- Bid price dictates the minimum price difference required for a virtual link to participate.
- The more allocation a virtual link gets, the less the price difference is across the virtual link.
- There is value in expanding the capacity of a virtual link only if the allocation uses up all existing capacity of a virtual link.

These properties bring up some interesting guidance on how flexibility providers should invest and operate their flexibility. Specifically, there exist trade-offs for the choice of bid price and capacity. A higher bid price guarantees a higher minimum profit, but reduces the chance of winning the bid (and actually earning the money). A larger bid capacity may risk reducing the unit profit, while a smaller bid capacity may risk losing revenue due to inability to sell more flexibility. These trade-offs are evident from the case studies in (Zhang and Zavala, 2021). Figure 4 shows the results for one of the case studies, demonstrating how large amount of flexibility bit into the market wipes out price volatility in both space and time (and also profit for flexibility providers). The optimal operation for flexible loads will happen somewhere between these two extreme cases, where bid capacity is right at the sweet spot that generates much profit without eliminating unit profit. To find such optimal operations, studies on strategic bidding under this market are needed, which often lead to a bilevel optimization framework between the flexible loads and the ISO.

Extension to Storage Systems

In this section, we demonstrate how the concept of virtual links can be extended to energy storage resources (ESRs), a more complicated type of flexibility providers (Zhang et al., 2022). Storage systems can provide power shifting flexibility in time by charging and discharging at different times. First, we introduce a common operation model used for incorporating storage in energy-only markets:

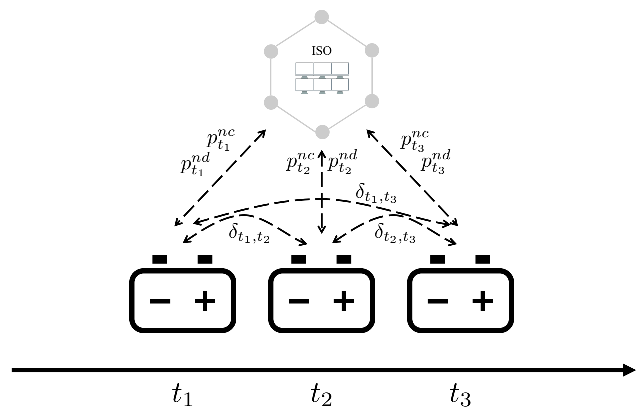


Figure 5: Virtual link modeling of storage systems.

$$\Delta \underline{s}_{b,t} \leq \eta_b^c \sum_{t'=1}^{t} p^c_{b,t'} - \frac{1}{\eta_b^d} \sum_{t'=1}^{t} p^d_{b,t'} \leq \Delta \bar{s}_b,\ t \in \mathcal{T} \tag{3a}$$

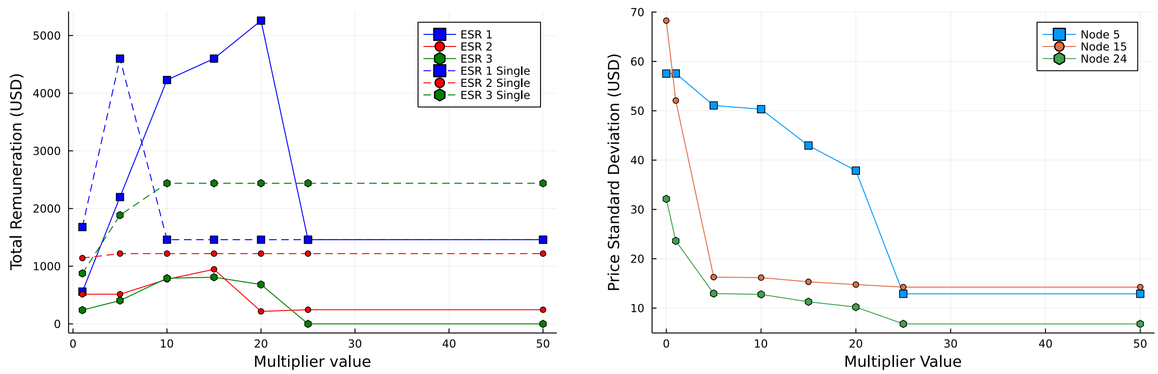
$$p^c_{b,t} + p^d_{b,t} \leq \bar{p}_b,\ t \in \mathcal{T} \tag{3b}$$

$$0 \leq p^c_{b,t} \perp p^d_{b,t} \geq 0,\ t \in \mathcal{T} \tag{3c}$$

where b denotes storage unit, $t, t' \in \mathcal{T}$ denote time, $p^c_{b,t}/p^d_{b,t}$ are charging/discharging power of b at t. The constraints capture the energy capacity, power capacity and charge/discharge complementarity constraints. Note that the model accounts for power loss using efficiency parameters $\eta_b^c, \eta_b^d \in [0,1]$. With some tightening methods to get rid of complementarity constraints (Nazir and Almassalkhi, 2021), the storage operation model (3) can be embedded directly into a standard market clearing framework (i.e. model (1) with no virtual links). However, we will demonstrate that applying virtual link concept for capturing flexibility from storage systems sheds light on how physical properties of storage systems affect the market behavior.

To apply virtual links to capture power shifting flexibility of storage systems, we note that from the perspective of market interaction, the operations of storage systems can be broken down into three categories:

1. *Net-charging:* buying an amount of electricity from the



(a) Total remuneration

(b) Price volatility

Figure 6: Total remuneration and price volatility of each ESR at different level of bid capacity (denoted by multiplier value). Solid lines are obtained from the solution where all ESRs simultaneously participate in the market, and dashed lines ("Single" in legend) are obtained from solutions where each ESR solely participates in the market with 3 times higher capacity.

market at a time period and storing it for the rest of the period.

2. *Net-discharging:* selling an amount of electricity to the market at a time period that will not be replaced by electricity purchase later.

3. *Energy transfer:* moving certain amount of energy from one time to another time. This captures charging/discharging certain amount of electricity at one time and discharging/charging it later.

In one market clearing period, at most one of net-charging and net-discharging will happen. The power shifting flexibility only occurs with energy transfer. In model (3), all these operations are mixed up in charging and discharging decisions. With virtual links, we are able to capture energy transfer explicitly, where a virtual link going from t_1 to t_2 means charging at t_1 and discharging at t_2. This modeling rationale is illustrated in figure 5.

Formally, we can replace the charging and discharging $p^c_{b,t}, p^d_{b,t}$ variables as follows:

$$p^c_{b,t} = \sum_{v \in \mathcal{V}^{\text{out}}_{b,t}} \delta_v + p^{nc}_{b,t} \tag{4a}$$

$$p^d_{b,t} = \sum_{v \in \mathcal{V}^{\text{in}}_{b,t}} \eta_{b(v)} \delta_v + p^{nd}_{b,t} \tag{4b}$$

where $\eta_b := \eta^c_b \cdot \eta^d_b$, $p^{nc}_{b,t}/p^{nd}_{b,t}$ are variables for net-charging/discharing power. Applying this transformation gives rise to the final market model, which we will not show here due to space limit (more details can be found in work of Zhang et al. (2022)). Following the same Lagrangian duality analysis shows that the optimal solution of the corresponding market clearing model maximizes the total profit for each storage system, which is defined as follows:

$$\begin{aligned}\phi_b \quad &= \sum_{v \in \mathcal{V}_b} (\eta_b \pi^d_v - \pi^c_v - \alpha^\delta_v)\delta_v \\ &+ \sum_{t \in \mathcal{T}} \left[(\pi_{b,t} - \alpha^{sd}_{b,t}) p^{nd}_{b,t} - (\pi_{b,t} + \alpha^{sc}_{b,t}) p^{nc}_{b,t} \right]\end{aligned} \tag{5}$$

Here we make some observation about the behavior of the storage systems. First, net-charging and net-discharging generally occur when the prices do not exhibit too much volatility over the market time period; either the prices are universally low or high. In terms of energy transfer, under this framework, the profit function for each virtual link v is $(\eta_b \pi^d_v - \pi^c_v - \alpha^\delta_v)\delta_v$, slightly different from (2b). This is the key mechanism of how physical property of the storage system affects the market and pricing behavior under our framework. In order to make a single virtual link v profitable (thus activating the virtual link), the price difference needs to be as large as follows:

$$\eta_b \pi^d_v - \pi^c_v - \alpha^\delta_v \geq 0 \Rightarrow \pi^d_v - \pi^c_v \geq \frac{1-\eta_b}{\eta_b}\pi^c_v + \frac{1}{\eta_b}\alpha^\delta_v \tag{6}$$

This shows two important lessons for incorporating flexibility from storage:

- The less efficient the storage is, the large the price difference needs to be. Ideally when $\eta_b = 1$, the price difference only needs to cover bid price (we recover (2b) as the profit function for a single virtual link).

- In order to activate the virtual link, the price difference has to be much larger if the prices generally reside in a high region (i.e. if π^c_v is high). This makes harnessing flexibility difficult at high price levels and may provide a driving force towards lower prices over the market.

We note that the trade-off effect for bidding strategy is observed for storage systems as well. The solid lines in figures 6a and 6b show that bidding more capacity reduces the price volatility but increases the allocation for flexibility, which overall leads to the optimal remuneration happening somewhere in the middle of the bid capacity range. In addition, we also observe from figures 6a and 7 that ISO and storage providers have conflicting preference on the extent of (de)centralization for storage. Specifically, ISOs prefer more decentralized storage systems as a large number of small ESRs lead to the lowest price volatility across all nodes. On the other hand, storage system owners might be inclined to

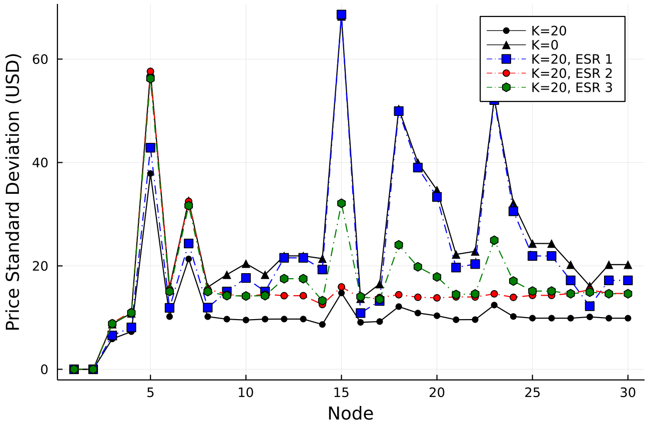


Figure 7: Temporal standard deviation of nodal prices for bid capacity multiplier K = 0, K = 20, and K = 20 with individual ESR participation. The solid line with K = 20 denotes the case where all storage systems participate simultaneously, and the dashed lines denote the case where only one storage participates (participating storage is denoted in legend).

have a large storage unit instead, which possibly generates higher remuneration, as shown by the difference between solid and dashed lines in figure 6a. This implies that with equal total capacity, decentralized energy storage capacity across multiple locations provide more flexibility to the market compared to centralized capacity. This makes intuitive sense as more decentralized storage helps provide flexibility across more locations compared to one single centralized storage.

Conclusion

In this work we introduce virtual links, a new market design concept for capturing shifting flexibility from modular manufacturing and storage systems. We argue that such new market design facilitates flexibility provision in energy markets by opening up new revenue streams for flexibility providers. Under market designs based on virtual links, we demonstrate how strategic bidding is important for flexibility providers due to the trade-off between maintaining high allocation versus maintaining high profit for each unit of flexibility sold to the market. In the case of storage, virtual link model reveals how physical properties of storage systems could affect the market behavior. We also show how market designs based on virtual links reveal benefits of energy storage decentralization for ISOs.

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