Using Storage-Capacity Rights to Overcome the Cost-Recovery Hurdle for Energy Storage

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***Abstract*—Energy storage is unique in that it can provide multiple services. This feature raises cost-recovery issues for storage, due to the combination of competitive markets and ratebased cost-recovery used in many power systems today. This hybrid regulatory paradigm relies on classifying assets as providing competitively prices or unpriced services and handling cost recovery based on that classification. Some recent regulatory precedents suggest that storage developers must choose between classifying their assets as providing competitively priced or unpriced services. In the former case, storage costs must be recovered through the market. If an asset is classified as providing *only* unpriced services, costs can be recovered through the ratebase.**

This regulatory design can hamper cost-recovery for storage and may lead to inefficient storage investment and use. We propose an alternate solution whereby storage-capacity rights are auctioned to third parties that use their rights for priced or unpriced services. Storage-capacity rights disentangle storage cost recovery from the regulatory treatment of its end use. We formulate the storage-capacity auction model and demonstrate how to efficiently price storage-capacity rights. We show that the revenues earned by the storage owner through the auction equals the imputed marginal value of storage capacity, as revealed by the market bids.

***Index Terms*—Energy storage, market design, pricing**

NOMENCLATURE

A. Sets and Parameters

H	hours of storage capacity.
$M_{t,t'}$	set of bids submitted for energy-capacity rights with an hour-t injection and hour-t' withdrawal (with $t' > t$).
N_t	set of bids submitted for hour-t power-capacity rights.
$Q^c_{t,n}$	MW in nth hour-t power-capacity charging bid.
$Q^d_{t,n}$	MW in nth hour-t power-capacity discharging bid.
$Q^e_{t,t',m}$	MW in mth energy-capacity bid with an hour-t injection and hour-t' withdrawal (with $t' > t$).
$\bar{R}$	storage power capacity [MW].
T	number of hours in storage-capacity auction.
η^c	charging efficiency of storage.
η^s	carrying efficiency of storage.
$\pi^c_{t,n}$	price of nth hour-t power-capacity charging bid [\$/MW].
$\pi^d_{t,n}$	price of nth hour-t power-capacity discharging bid [\$/MW].
$\pi^e_{t,t',m}$	price of mth energy-capacity bid with an hour-t injection and hour-t' withdrawal (with $t' > t$) [\$/MW].

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B. Variables

$q^c_{t,n}$	MW of nth hour-t power-capacity charging bid accepted.
$q^d_{t,n}$	MW of nth hour-t power-capacity discharging bid accepted.
$q^e_{t,t',m}$	MW of mth energy-capacity bid with an hour-t injection and hour-t' withdrawal (with $t' > t$) accepted.
s_t	ending hour-t state of charge of storage device.

I. INTRODUCTION

RECENT developments in the electricity industry have increased the interest in the development, deployment, and use of energy storage technologies. Among these, the past two decades have seen the introduction of restructured electricity markets, which provide prices that value many of the services that storage can provide. There is also a growing recognition that storage can provide many more benefits than generation shifting and generation-capacity deferral, which were the primary rationales for storage development in the 1970s. Comprehensive surveys of the applications that storage can be used for are in the literature [1]–[3] and we can classify these potential uses of storage into the following seven broad categories:

1) Energy arbitrage: store low-cost energy which is discharged and sold when cost is higher
2) Generation capacity deferral: store energy when excess generating capacity is available and discharge it when capacity is limited
3) Ancillary services (AS): use stored energy to provide frequency regulation, contingency reserves, or black start
4) Ramping: follow hourly or subhourly changes in system load
5) Transmission and distribution capacity deferral: store energy when transmission or distribution capacity is available and discharge it when capacity is limited
6) Power quality and service reliability: improve power quality (*e.g.*, voltage, frequency, and harmonics) or use stored energy as a backup energy source during a service disruption
7) Renewable curtailment: store renewable energy that would otherwise be curtailed due to generation operational or transmission constraints and discharge energy when such constraints are non-binding

It is important to stress, however, that not all storage technologies are suitable to providing all of these services [1]–[3].

Storage faces important regulatory and cost-recovery issues in restructured market settings [4]. These issues arise because restructured electricity markets have a hybrid regulatory structure. This hybrid regulatory structure means that some electricity-related services, *e.g*., the provision of energy, are priced in competitive markets. The cost of services that are priced in the market are assumed to be recovered through these price signals. Other services, *e.g*., installation and maintenance of distribution equipment, is not amenable to market competition. The cost of such services that are not priced in the market are typically recovered through the rate base.

This hybrid regulatory paradigm has hitherto been largely successful, because most assets can be classified as primarily providing services that are either competitively priced or not. Energy storage is not conducive to this hybrid regulatory model, however. This is because storage can provide services that are both priced in competitive markets and not. Recent regulatory precedents in the United States have pointed toward forcing storage developers to choose between either providing services that are competitively priced or those that are not. If a storage developer opts for the former, costs are expected to be recovered through competitive prices. In doing so, a storage developer is unable to capture the value of any services it provides that are not priced in the market. If a storage developer chooses the latter option, it is legally precluded from providing services that are competitively priced.

In this paper we propose a new market design for energy storage that surmounts the regulatory and cost-recovery issues that storage faces. Our proposal is to competitively auction storage-capacity rights to third parties, which can use their capacity rights for services that are competitively priced or subject to ratebased cost recovery. By auctioning the storage capacity rights in this way, cost recovery of storage services that are competitively priced and those that are ratebased do not interfere with one another. We show that our proposed market design aligns the incentives of the third parties to efficiently use scarce storage capacity. Moreover, we show that the market design allows the storage owner to capture the imputed marginal value of storage capacity through the auction.

It should be stressed that many storage technologies have near-zero operational costs. Thus, in most cases this discussion is centered around investment-cost recovery. However, to the extent that some technologies (*e.g*., compressed-air energy storage) have non-trivial operating costs, recovery of those costs is also at issue here.

The remainder of this paper is organized as follows. In Section II we summarize the storage-related regulatory precedents in the United States and discuss the implications and issues that they raise for efficient storage investment and use. Section III introduces our proposed market design and provides a theoretical examination of its properties. Section IV provides two numerical examples that further demonstrate how the proposed market functions. Section V concludes with some further discussion of our proposed market design.

II. Storage-Related Regulatory Decisions

Restructured electricity markets are in practice a hybrid design combining competitive markets with cost-of-service regulation. This is because the provision of some services, such as energy, AS, and generation capacity, is conducive to a competitive price-setting process. Other services are not, because of natural monopolies, theoretical market-design problems, or because market designs do not function well in practice. Although they are not the only cases taken up by the Federal Energy Regulatory Commission (FERC), we begin by examining two storage-related FERC cases and the precedents that they set for investment and cost-recovery of energy storage assets in light of this hybrid regulatory design.

The first involves the 500 MW Lake Elsinore Advanced Pumping Station (LEAPS) plant in Southern California, which was proposed by Nevada Hydro.[1] Nevada Hydro proposed building the LEAPS plant along with a new transmission corridor between the Southern California Edison and San Diego Gas and Electric service territories. The two projects were proposed to relieve chronic transmission constraints into the San Diego region. The LEAPS plant would supplement the transmission upgrade by storing energy when the transmission corridor is unconstrained and discharging energy to relieve the constraint when the corridor is congested. Because of its transmission benefits, Nevada Hydro requested that its investment costs be ratebased. It also proposed an arrangement whereby the California ISO (CAISO) dispatches the LEAPS plant to maximize its transmission-relief benefits.

In its ruling, the FERC allowed the cost of the transmission corridor *only* to be ratebased but denied Nevada Hydro's other requests. The FERC concluded that the CAISO dispatching the LEAPS plant would be akin to the CAISO owning and operating generation and could threaten the independence required of a market operator. This is because the CAISO would be affecting market prices through its LEAPS-dispatch decisions. This market-independence issue was in fact an objection raised by the CAISO in its filings in the case.[2] Moreover, the FERC concluded that the LEAPS plant would be offering transmission services that are captured in the wholesale market through locational marginal prices. Thus, it would be inappropriate to ratebase the cost of the LEAPS plant, which should instead recover its costs through the wholesale market.

The second case involves a set of batteries that Western Grid planned to build in California.[3] Western Grid proposed building the batteries to address thermal overloads and to provide voltage support and other transmission-related services. As in the LEAPS case, Western Grid requested that the cost of the batteries be ratebased, citing their transmission-related benefits. Unlike in the LEAPS case, Western Grid was explicit in stating that the batteries would be used *solely*

[1] See FERC docket numbers ER06-278-000 through ER06-278-006 for all of the filings and rulings in this case.

[2] *cf*. page 7 of the FERC's Order on Rate Incentives and Compliance Filings in this case where the FERC expressly directs the CAISO to address 'whether CAISO can effectively operate [LEAPS] in the context of being an independent system operator.' Pages 24 and 25 provide the CAISO's response, in which the 'CAISO submits that, based on stakeholder input and its own evaluation of the issues ... CAISO should not assume operational control of the LEAPS facility,' and 'that any transfer of control analyzed in [the] proceeding would compromise CAISO's independence as envisioned in [FERC] Order No. 2000.'

[3] See FERC docket number EL10-19-000 for all of the filings and rulings in this case.

for transmission-related services that are not priced in any market. Instead, the batteries would be operated solely on the basis of administrative instructions provided by the CAISO. As such, the batteries would be operated in the same manner as capacitors that are used to address transmission issues and would not threaten the CAISO's market independence. In doing so, Western Grid explicitly precluded the possibility of using the batteries for any energy or AS services, as those services are priced in the market. Unlike in the LEAPS case, the FERC allowed the cost of the batteries to be ratebased.

Taken together, these two decisions raise some issues regarding cost recovery for energy storage that have important implications for efficient investment in and use of storage. Contrasting the decisions in the LEAPS and Western Grid cases suggests that a storage developer must make a conscious decision of whether to *only* offer services that are not priced in the market or to offer services that are priced. If the developer chooses the former, the Western Grid case suggests that investment and other costs can be ratebased. This is beneficial to the developer because ratebased investments tend to have lower risk than assets that must recover costs in a competitive market.

Deploying a storage asset that only provides unpriced services can result in inefficient asset use, however. As an example of this, take the batteries proposed in the Western Grid case and consider a day on which the energy stored in the batteries is not needed for transmission-related services. Because the batteries are not needed for transmission-related services (and would, thus, remain idle), it could be beneficial to discharge the batteries if energy or AS prices are sufficiently high. Doing so would be beneficial to the battery owner, as reflected in the market revenues that would be earned. This use of the battery is also socially beneficial, as it allows lower-cost energy that has already been charged into the battery to displace higher-cost energy that would otherwise be used when the market price is high [5]. However, to receive ratebased cost recovery, Western Grid explicitly precluded the possibility of using the battery to provide any service that is priced in the market in its filings. The ruling in the LEAPS case suggests that Western Grid may not have received ratebased cost recovery without this explicit stipulation. This creates a clear operational inefficiency, as the asset must sit idle when it could provide a socially and privately valuable service. Indeed, one of the objections that the CAISO raised to ratebased cost recovery in the Western Grid case is that it would force ratepayers to cover the cost of batteries that would not be used to their full potential.[4] However, this limitation of using the batteries only for unpriced services was needed to ensure ratebased cost recovery.

This limitation on capturing market-priced value by storage assets providing unpriced services can also hinder efficient storage investment. This is because storage may be a more costly alternative to a transmission- or distribution-capacity upgrade when considering capacity deferral *only*. However, if a distributed storage asset can provide energy and AS in addition to capacity deferral, it may be a more economic solution in net [6]. The Western Grid and LEAPS decisions suggest, however, that a distributed energy storage system may not be able to capture energy and AS revenues while also having proper rate treatment of its capacity-deferral benefits.

Interestingly, the inability of the batteries in the Western Grid case to capture energy and AS revenues while receiving ratebased cost recovery ultimately became a hindrance to the project being deployed. In its ruling on the case, the FERC required the CAISO to evaluate the Western Grid proposal as an alternative to traditional transmission upgrades (in line with FERC Order 890). The CAISO determined that the Western Grid batteries were not the most prudent transmission-upgrade option. If the batteries could have provided energy or AS to defray part of their investment costs, they may have been selected as the most prudent alternative.

The alternate option for a storage developer is to provide services priced in the market *only*, thereby foregoing ratebasing of the asset cost. If a storage asset is being built solely or primarily to provide services priced in the market, this can be a viable option. A real-world example of this is more than 300 MW of flywheel and battery projects developed to provide frequency regulation reserves [4]. An important limitation of this storage-development paradigm, however, is that it does not allow for storage to provide a combination of services. As an example, a storage asset may not be economically prudent on the basis of frequency regulation revenues alone. However, if it could capture the value of transmission-deferral benefits in addition to frequency regulation revenues, it may be a prudent investment. The LEAPS decision suggests that such co-mingling of priced and unpriced services will not be allowed by the FERC.

The FERC's decision not to ratebase the cost of the LEAPS plant stems from a fundamental principal underlying competitive wholesale electricity market design. The market produces price signals that drive the system toward an equilibrium that is short- and long-run efficient. The resulting efficiency of the market is premised, in part, on the assumption that assets competing in the wholesale market recover their costs through market revenues. If subsidies or other market distortions eliminate this competitive pressure, the price-formation process may not yield market efficiency. Similarly, ratebasing the LEAPS plant and allowing it to participate in the wholesale market can harm price formation.

This issue of price formation with a subsidized storage asset has also been playing out in the state of Texas. In November, 2014 Oncor, a transmission and distribution utility, proposed building 5 GW of distributed storage in the state of Texas. This proposal was based on an analysis suggesting that 5 GW of storage could justify its investment cost through the range of services that it could provide [7].

A question that was immediately raised by this proposal was whether storage assets owned by a regulated transmission and distribution utility, which would likely received rate-based cost recovery, could participate in the wholesale ERCOT markets for energy and AS. This was a particularly important issue in Texas, because ERCOT operates as an energy-only market. Unlike the New York ISO, ISO New England, and PJM

[4] *cf.* Page 12 of the FERC's Order on Petition for Declaratory Order in the Western Grid case.

markets, there is no capacity product in ERCOT. As such, generators must recover their costs solely through scarcity pricing in the energy and AS markets. Storage assets receiving rate-based cost recovery participating in these markets could dampen scarcity prices, threatening future generation investment.

Legislation and regulatory rulings at the time of Oncor's proposal precluded a transmission and distribution utility owning assets (*e.g.*, generation) that participate in the wholesale ERCOT markets. As a result, Oncor has not yet proceeded with its proposal. According to Oncor, if storage assets are limited to providing voltage support, backup energy, and distribution capacity deferral (which are standard services provided by transmission and distribution utilities) but cannot provide market-priced services, such as energy arbitrage and frequency regulation, their financial viability is limited.

III. Storage-Capacity Auction

Section II suggests that any regulatory and cost-recovery paradigm for energy storage should ideally satisfy three properties. First, it should allow a storage asset to capture the value of *all* of the services that it could potentially provide, regardless of whether they are priced in a competitive market or not. Second, it should not rely on the market operator dispatching the storage asset in a manner that threatens its market independence. Finally, it should not introduce any subsidies or other distortions to the price-formation process in competitive markets.

Our proposed solution to the issues raised in Section II is to extend the model proposed by He *et al*. [8] to aggregate multiple uses of energy storage. The heart of our proposal is to introduce a market that competitively auctions storage-capacity rights to independent third parties that do not own the storage asset. The purpose of this auction is to ration storage capacity between different potential uses, some of which may be priced in the market while others are not.

As a very simple illustrative example of our proposal, suppose that a 1 MW distributed battery with one hour of storage capacity is available for use during a one-day period. There are two parties that are interested in using the battery capacity. The first would like to use the battery to arbitrage on- and off-peak electricity price differences. It would value this use of the battery at $\eta \cdot p^n - p^f$, where p^n and p^f are on- and off-peak electricity prices, respectively, and η is the roundtrip efficiency of the battery. The second party would like to use the battery to relieve the loading on a distribution transformer. It would value this use of the battery at $V^t - p^c$, where V^t is the avoided transformer aging cost from relieving the transformer and p^c is the cost of charging energy into the battery.

These two parties, neither of which owns the battery, compete with one another in our proposed auction for the right to use the storage capacity. The storage capacity is allocated to whichever of the two parties has a higher bid, which may vary from day to day. If the storage capacity is allocated to the first party, the cost of acquiring the capacity is recovered through energy-arbitrage revenues earned in the market. This is because the first party uses the battery for a service that is competitively priced. If the second party wins the storage-capacity auction, the acquisition cost could be recovered through the ratebase. This is because the second party uses the battery for distribution-capacity deferral, which is not a competitively priced service.

The benefit of the storage-capacity auction is that it disentangles cost recovery of the storage asset from the regulatory and rate treatment of different end uses. This is done by having third parties use storage capacity for different applications. Each of these third parties handles cost recovery on its own, depending on the particular application each one uses its storage allocation for.

Unlike the simple example given above, in practice a storage asset can simultaneously be used by multiple parties for multiple uses [8]. Thus, we generalize the storage-capacity auction by introducing two types of storage-capacity products: power-capacity and energy-capacity rights. A power-capacity right entitles the holder to either inject or withdraw energy into or out of the storage device in a particular hour. A power-capacity right could be used, for instance, by a party that intends to use storage for energy arbitrage. This is because energy arbitrage requires an energy injection and withdrawal at specific points in time. The state of charge (SOC) of the storage device between the injection and withdrawal are immaterial to a party using storage for energy arbitrage, so long as it can make the desired injections and withdrawals.

An energy-capacity right entitles the holder to an injection and withdrawal of energy at specific points in time and ensures that the injected energy remains in storage between the injection and withdrawal times. An energy-capacity right could be useful, for example, to a party that intends to use storage for backup energy in the event of a system contingency. This is because using storage as a backup energy source requires the SOC to remain above a certain threshold between the injection and withdrawal times. If a system contingency occurs within this time window, the holder of an energy-capacity right can use the stored energy to mitigate the contingency.

A. Storage-Capacity Auction Model

We now provide a stylized version of the storage-capacity auction, based on a generic storage model [9], [10], which we use to examine the properties of the proposed auction. We also discuss some possible extensions of the model and the specific definitions of the storage-capacity products used. For ease of exposition, we assume throughout that storage operations and storage-capacity rights are modeled at hourly intervals. Our market design is agnostic to the timestep, however. In practice the auction could be designed to allocate rights at coarser or more granular timesteps.

We measure the capacity of the storage device in terms of its power capacity, which we denote as $\bar{R}$, and the number of hours of storage, H. We assume that the power capacity is measured in MW, as these are the units typically used for specifying prices and quantities in wholesale electricity markets. We measure the efficiency of the storage plant using two parameters, η^c and η^s, which are the charging and carrying efficiencies of the device.

We assume that there are three types of storage-capacity bids. The first two are for power-capacity rights, which take the form of either charging or discharging bids. We let N_t denote the index set for bids submitted for hour-t power-capacity rights. Each charging and discharging bid consists of a price and quantity indicating the maximum amount that the bidder would like to inject or withdraw from storage and the maximum or minimum price at which it would be willing to do so. The third type of bid is for an energy-capacity right, which specifies injection and withdrawal hours. We let $M_{t,t'}$ be an index set for bids submitted for energy-capacity rights with an injection and withdrawal of energy in hours t and t', respectively. As with the power-capacity bids, energy-capacity bids also specify a maximum quantity and price. We use the convention that the quantity portion of the bid for an energy-capacity right specifies the amount of energy that is withdrawn in hour t'. Thus, if $q^e_{t,t',m}$ MW of energy-capacity rights clear the auction, this means that the holder of the right is entitled to withdraw $q^e_{t,t',m}$ MW in hour t'. This party must also inject:

$$\frac{q^e_{t,t',m}}{\eta^c \cdot (\eta^s)^{(t'-t)}}, \tag{1}$$

MW in hour t, to account for efficiency-related energy losses between the injection and withdrawal hours. One could define energy-capacity rights in terms of how much energy is injected. So long as the auction model and pricing rules account for the convention used in defining these rights, our two results regarding the storage-capacity auction will hold.

We do not assume that power-capacity charging and discharging bids are 'coupled' with one another. As a result, a party may have a charging or discharging bid that clears the market but no corresponding discharging or charging bid that clears. An obvious shortcoming of this is that a bidder wishing to use the storage device for a service that does not require an energy-capacity right (*e.g.*, energy arbitrage) may not have both the injection and withdrawal clear together. One could address this issue by adding a fourth power-capacity product that consists of coupled injections and withdrawals (but without a right to the stored energy between the injection and withdrawal times). We do not include such a product to simplify the auction model and analysis. However, our results showing efficiency of the proposed market design easily extend to a setting with such a product. Otherwise, without a coupled power-capacity product, a bidder could address an unmatched bid by buying or selling storage-capacity rights bilaterally or in a reconfiguration auction, as is common practice in many electricity markets today (*e.g.*, hour-ahead and real-time energy and AS markets, incremental auctions for generation capacity, and reconfiguration auctions for financial transmission rights).

We define $q^c_{t,n}$, $q^d_{t,n}$, and $q^e_{t,t',m}$ as continuous variables giving the allocation of storage-capacity rights. We implicitly assume that the bids for power- and energy-capacity rights allow the auctioneer to allocate any amount up to the quantity specified in the bid (*i.e.*, up to $Q^c_{t,n}$, $Q^d_{t,n}$, or $Q^e_{t,t',m}$). This is as opposed to assuming that storage-capacity rights must be allocated in fixed amounts equal to the quantities in each of the bids. The efficiency results of our proposed market design require this assumption, to maintain convexity of the capacity-auction model.

The capacity-auction model is formulated as:

$$\max_{q,s} \sum_{t=1}^{T} \sum_{n \in N_t} (\pi^d_{t,n} q^d_{t,n} - \pi^c_{t,n} q^c_{t,n}) \tag{2}$$
$$+ \sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \pi^e_{t,t',m} q^e_{t,t',m}$$

$$\text{s.t. } s_t = \eta^s s_{t-1} + \sum_{n \in N_t} (\eta^c q^c_{t,n} - q^d_{t,n}) \tag{3}$$
$$+ \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \eta^c q^e_{t,t',m} - \sum_{t'=1}^{t-1} \sum_{m \in M_{t',t}} q^e_{t',t,m},$$
$$\forall t = 1, \ldots, T; \qquad (\lambda_t)$$

$$\sum_{t'=1}^{t} \sum_{t''=t+1}^{T} \sum_{m \in M_{t',t''}} q^e_{t',t'',m} \le s_t \le H \cdot \bar{R}, \tag{4}$$
$$\forall t = 1, \ldots, T; \qquad (\sigma^-_t, \sigma^+_t)$$

$$-\bar{R} \le \sum_{n \in N_t} (\eta^c q^c_{t,n} - q^d_{t,n}) + \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \eta^c q^e_{t,t',m}$$
$$- \sum_{t'=1}^{t-1} \sum_{m \in M_{t',t}} q^e_{t',t,m} \le \bar{R}, \tag{5}$$
$$\forall t = 1, \ldots, T; \qquad (\gamma^-_t, \gamma^+_t)$$

$$0 \le q^c_{t,n} \le Q^c_{t,n}, \tag{6}$$
$$\forall t = 1, \ldots, T; n \in N_t; (\mu^{c,-}_{t,n}, \mu^{c,+}_{t,n})$$

$$0 \le q^d_{t,n} \le Q^d_{t,n}, \tag{7}$$
$$\forall t = 1, \ldots, T; n \in N_t; (\mu^{d,-}_{t,n}, \mu^{d,+}_{t,n})$$

$$0 \le q^e_{t,t',m} \le Q^e_{t,t',m}, \tag{8}$$
$$\forall t, t' = 1, \ldots, T; t' > t; m \in M_{t,t'};$$
$$(\mu^{e,-}_{t,t',m}, \mu^{e,+}_{t,t',m})$$

where the Lagrange multipliers associated with each constraint set are indicated in the parentheses to the right of it. Objective function (2) maximizes the value of the allocation, based on the bids submitted. The:

$$\sum_{t=1}^{T} \sum_{n \in N_t} (\pi^d_{t,n} q^d_{t,n} - \pi^c_{t,n} q^c_{t,n}), \tag{9}$$

term in the objective function maximizes the value of withdrawing and injecting power into storage. This objective-function term results in the model 'connecting' charging and discharging power-capacity bids in some sense. That is to say, a charging power-capacity right is only allocated if there is a bid for a discharging power-capacity right that is sufficiently higher than the charging power-capacity right to make it economic to allocate both (when accounting for the efficiency losses, η^c and η^e). The:

$$\sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \pi^e_{t,t',m} q^e_{t,t',m}, \tag{10}$$

term in the objective maximizes the value of energy held in storage associated with the allocation of energy-capacity rights. This is embodied by the bids, $\pi^e_{t,t',m}$, submitted for energy-capacity rights.

Energy-balance constraints (3) define the ending hour-t SOC of the storage device in terms of the hour-$(t-1)$ SOC and the hour-t charging and discharging allocation. The charging-efficiency factor, η^c, is applied to energy charged into storage. The carrying-efficiency factor, η^s, is applied to the energy carried over from the previous hour.

Constraints (4) limit the SOC of the storage device in each hour based on the device's hours of storage capacity. The lower-bounds in these constraints are defined by the allocation of energy-capacity rights. This is because energy-capacity rights entitle the holder to stored energy between the injection and withdrawal hours. Thus, the SOC must be sufficiently high to ensure that all of these rights could be physically exercised in real-time between their injection and withdrawal hours. Our convention of having the energy-capacity right quantity defined in terms of withdrawn energy is embodied in the left-hand sides of these constraints. If energy-capacity rights are instead defined by the amount of energy that is injected, these constraints would instead have:

$$\sum_{t'=1}^{t}\sum_{t''=t+1}^{T}\sum_{m\in M_{t',t''}} \eta^c q^e_{t',t'',m}, \tag{11}$$

on their left-hand sides. Note that an energy-capacity right that consists of hour-t' charging and hour-t'' discharging *only* affects the minimum SOC between hours t' and t''.

Constraints (5) limit the amount of energy charged into or discharged from the storage device in net in each hour based on the device's power capacity. Finally, constraint sets (6)–(8) limit the allocation of power- and energy-capacity rights to each bid based on the quantity specified in each bid.

Our model assumes that there is no direct operational cost of using storage. This is because there are no variable cost terms in objective function (2). The only 'cost' of using storage is the difference between the value of the energy discharged and the cost of energy charged (which is reflected in the π's submitted by the bidders), and the value of energy lost due to the η^c and η^s efficiency terms. Many storage technologies have negligible direct operational costs, meaning that this assumption is reasonable. Some technologies (*e.g.*, compressed air energy storage) have non-trivial operational costs. Our model could be extended to include such costs and our main theoretical results would continue to hold, so long as the pricing rules for the storage-capacity rights are adjusted to account for these costs.

B. Properties of Storage-Capacity Auction

Because the storage-capacity auction model is a convex linear optimization problem, the Karush-Kuhn-Tucker (KKT) conditions are necessary and sufficient for a global optimum. The KKT conditions are:

$$\pi^c_{t,n} - \eta^c\lambda_t - \eta^c\cdot(\gamma^-_t - \gamma^+_t) - \mu^{c,-}_{t,n} + \mu^{c,+}_{t,n} = 0, \quad \forall t = 1,\ldots,T; n \in N_t; \tag{12}$$

$$-\pi^d_{t,n} + \lambda_t + \gamma^-_t - \gamma^+_t - \mu^{d,-}_{t,n} + \mu^{d,+}_{t,n} = 0, \quad \forall t = 1,\ldots,T; n \in N_t; \tag{13}$$

$$-\pi^e_{t,t',m} - \eta^c\lambda_t + \lambda_{t'} + \sum_{\tau=t}^{t'-1}\sigma^-_\tau - \eta^c\cdot(\gamma^-_t - \gamma^+_t) + \gamma^-_{t'} - \gamma^+_{t'} - \mu^{e,-}_{t,t',m} + \mu^{e,+}_{t,t',m} = 0, \quad \forall t,t' = 1,\ldots,T; t' > t; m \in M_{t,t'}; \tag{14}$$

$$\lambda_t - \eta^s\lambda_{t+1} - \sigma^-_t + \sigma^+_t = 0, \qquad \forall t = 1,\ldots,T; \tag{15}$$

$$s_t = \eta^s s_{t-1} + \sum_{n\in N_t}(\eta^c q^c_{t,n} - q^d_{t,n}) + \sum_{t'=t+1}^{T}\sum_{m\in M_{t,t'}}\eta^c q^e_{t,t',m} - \sum_{t'=1}^{t-1}\sum_{m\in M_{t',t}} q^e_{t',t,m}, \quad \forall t = 1,\ldots,T; \tag{16}$$

$$\sum_{t'=1}^{t}\sum_{t''=t+1}^{T}\sum_{m\in M_{t',t''}} q^e_{t',t'',m} \le s_t \perp \sigma^-_t \ge 0, \quad \forall t = 1,\ldots,T; \tag{17}$$

$$s_t \le H\cdot\bar{R} \perp \sigma^+_t \ge 0, \qquad \forall t = 1,\ldots,T; \tag{18}$$

$$-\bar{R} \le \sum_{n\in N_t}(\eta^c q^c_{t,n} - q^d_{t,n}) + \sum_{t'=t+1}^{T}\sum_{m\in M_{t,t'}}\eta^c q^e_{t,t',m} - \sum_{t'=1}^{t-1}\sum_{m\in M_{t',t}} q^e_{t',t,m} \perp \gamma^-_t \ge 0, \quad \forall t = 1,\ldots,T; \tag{19}$$

$$\sum_{n\in N_t}(\eta^c q^c_{t,n} - q^d_{t,n}) + \sum_{t'=t+1}^{T}\sum_{m\in M_{t,t'}}\eta^c q^e_{t,t',m} - \sum_{t'=1}^{t-1}\sum_{m\in M_{t',t}} q^e_{t',t,m} \le \bar{R} \perp \gamma^+_t \ge 0, \quad \forall t = 1,\ldots,T; \tag{20}$$

$$0 \le q^c_{t,n} \perp \mu^{c,-}_{t,n} \ge 0, \qquad \forall t = 1,\ldots,T; n \in N_t; \tag{21}$$

$$q^c_{t,n} \le Q^c_{t,n} \perp \mu^{c,+}_{t,n} \ge 0, \qquad \forall t = 1,\ldots,T; n \in N_t; \tag{22}$$

$$0 \le q^d_{t,n} \perp \mu^{d,-}_{t,n} \ge 0, \qquad \forall t = 1,\ldots,T; n \in N_t; \tag{23}$$

$$q^d_{t,n} \le Q^d_{t,n} \perp \mu^{d,+}_{t,n} \ge 0, \qquad \forall t = 1,\ldots,T; n \in N_t; \tag{24}$$

$$0 \le q^e_{t,t',m} \perp \mu^{e,-}_{t,t',m} \ge 0, \quad \forall t,t' = 1,\ldots,T; t' > t; m \in M_{t,t'}; \tag{25}$$

$$q^e_{t,t',m} \le Q^e_{t,t',m} \perp \mu^{e,+}_{t,t',m} \ge 0, \quad \forall t,t' = 1,\ldots,T; t' > t; m \in M_{t,t'}; \tag{26}$$

where '$\perp$' indicates complementary slackness between a constraint and its corresponding Lagrange multiplier.

From analyzing these KKT conditions we derive our two main results. The first regards how to price storage-capacity rights, thereby ensuring that storage capacity is used efficiently by the third parties. Our second result shows that the profit earned by the storage owner from allocating storage rights captures the imputed marginal value of storage capacity. For notational convenience, we define q^c, q^d, q^e, and s as the decision variables in vector form and λ, σ^-, σ^+, γ^-, γ^+, $\mu^{c,-}$, $\mu^{c,+}$, $\mu^{d,-}$, $\mu^{d,+}$, $\mu^{e,-}$, and $\mu^{e,+}$ as the Lagrange multipliers in vector form.

Proposition 1: Suppose $\bar{q}^c$, $\bar{q}^d$, $\bar{q}^e$, $\bar{s}$, $\bar{\lambda}$, $\bar{\sigma}^-$, $\bar{\sigma}^+$, $\bar{\gamma}^-$, $\bar{\gamma}^+$, $\bar{\mu}^{c,-}$, $\bar{\mu}^{c,+}$, $\bar{\mu}^{d,-}$, $\bar{\mu}^{d,+}$, $\bar{\mu}^{e,-}$, and $\bar{\mu}^{e,+}$ satisfy KKT conditions (12)–(26). Consider the following per-MW pricing rules for storage-capacity rights: (i) hour-t power-capacity charging rights are priced at:

$$-\eta^c \lambda_t - \eta^c \cdot (\gamma_t^- - \gamma_t^+), \tag{27}$$

(ii) hour-t power-capacity discharging rights are priced at:

$$-\lambda_t - (\gamma_t^- - \gamma_t^+), \tag{28}$$

and (iii) energy-capacity rights consisting of an hour-t injection and hour-t' withdrawal are priced at:

$$\eta^c \lambda_t - \lambda_{t'} - \sum_{\tau=t}^{t'-1} \sigma_\tau^- + \eta^c \cdot (\gamma_t^- - \gamma_t^+) - (\gamma_{t'}^- - \gamma_{t'}^+). \tag{29}$$

Then the allocation of storage rights, $(\bar{q}^c, \bar{q}^d, \bar{q}^e)$, and the prices constitute an equilibrium in the sense that each storage-right owner would want to follow the injections and withdrawals specified by the allocation.

Proof: Consider an agent (that is independent of the storage owner) that would like to inject up to $Q_{\tau,i}^c$ MW in hour τ at a per-MW price of at most $\pi_{\tau,i}^c$ and withdraw up to $Q_{\tau',j}^d$ MW in hour τ' at a per-MW price of at least $\pi_{\tau',j}^d$. The agent would determine how much energy to charge in hour τ, which we denote by $x_{\tau,i}^c$, and how much to discharge in hour τ', which we denote by $x_{\tau',j}^d$, to maximize profit. Following the proposed pricing scheme, the agent solves the profit-maximization problem:

$$\max_x \; \left(\pi_{\tau',j}^d - \lambda_{\tau'} - (\gamma_{\tau'}^- - \gamma_{\tau'}^+)\right) x_{\tau',j}^d \tag{30}$$

$$- \left(\pi_{\tau,i}^c - \eta^c \lambda_\tau - \eta^c \cdot (\gamma_\tau^- - \gamma_\tau^+)\right) x_{\tau,i}^c$$

$$\text{s.t. } 0 \le x_{\tau,i}^c \le Q_{\tau,i}^c; \qquad (\mu_{\tau,i}^{c,-}, \mu_{\tau,i}^{c,+}) \tag{31}$$

$$0 \le x_{\tau',j}^d \le Q_{\tau',j}^d; \qquad (\mu_{\tau',j}^{d,-}, \mu_{\tau',j}^{d,+}) \tag{32}$$

where the Lagrange multiplier associated with each constraint is indicated in the parentheses to the right of it. Objective function (30) maximizes the value to the agent of the injection and withdrawal. The per-MW value of a withdrawal to the agent is $\pi_{\tau',j}^d$, however the agent must pay:

$$\lambda_{\tau'} + (\gamma_{\tau'}^- - \gamma_{\tau'}^+), \tag{33}$$

per MW withdrawn. Conversely, the agent incurs a per-MW cost of $\pi_{\tau,i}^c$ for storing energy, but is paid:

$$\eta^c \lambda_\tau + \eta^c \cdot (\gamma_\tau^- - \gamma_\tau^+), \tag{34}$$

per MW injected. The KKT conditions for the agent's problem are:

$$\pi_{\tau,i}^c - \eta^c \lambda_\tau - \eta^c \cdot (\gamma_\tau^- - \gamma_\tau^+) - \mu_{\tau,i}^{c,-} + \mu_{\tau,i}^{c,+} = 0; \tag{35}$$

$$-\pi_{\tau',j}^d + \lambda_{\tau'} + \gamma_{\tau'}^- - \gamma_{\tau'}^+ - \mu_{\tau',j}^{d,-} + \mu_{\tau',j}^{d,+} = 0; \tag{36}$$

$$0 \le q_{\tau,i}^c \perp \mu_{\tau,i}^{c,-} \ge 0; \tag{37}$$

$$q_{\tau,i}^c \le Q_{\tau,i}^c \perp \mu_{\tau,i}^{c,+} \ge 0; \tag{38}$$

$$0 \le q_{\tau',j}^d \perp \mu_{\tau',n}^{d,-} \ge 0; \tag{39}$$

$$q_{\tau',j}^d \le Q_{\tau',j}^d \perp \mu_{\tau',j}^{d,+} \ge 0. \tag{40}$$

Comparing KKT conditions (35)–(40) to conditions (12), (13), and (21)–(24) shows that the agent would optimally follow the charging and discharging allocation specified by the auctioneer (*i.e.*, the values of q's that are optimal in the auctioneer's problem are also optimal in the agent's problem). One can extend the agent's problem to include multiple blocks of charging and discharging demand over multiple periods and arrive at the same result. Moreover, adding demands for energy-capacity rights to the agent's profit-maximization problem would yield KKT conditions to the agent's problem that are the same as KKT conditions (14), (25), and (26) of the auctioneer's problem. ■

The pricing rule proposed in Proposition 1 has a very intuitive interpretation. A power-capacity charging right affects the storage device in two ways: it increases the device's SOC and contributes to the device's power constraints. The λ_t and $(\gamma_t^- - \gamma_t^+)$ terms in the price of the power-capacity charging right reflects these two effects. The charging efficiency, η^c, appears in the price because each MW charged into the device only contributes η^c MW toward the SOC and the power constraints. The pricing of a power-capacity discharging right can be interpreted in an analogous manner. A power-capacity discharging right decreases the storage device's SOC and contributes to the power constraints.

The self-discharging rate (which is captured in η^s) does not directly factor into the prices. Rather, it factors into the calculation of the λ Lagrange multiplier vector. This is because the self-discharge rate appears in KKT condition (15).

An energy-capacity right has the combined effect of power-capacity charging and discharging rights. This gives rise to the:

$$\eta^c \lambda_t - \lambda_{t'} + \eta^c \cdot (\gamma_t^- - \gamma_t^+) - (\gamma_{t'}^- - \gamma_{t'}^+), \tag{41}$$

terms in the energy-capacity right price. The:

$$-\sum_{\tau=t}^{t'-1} \sigma_\tau^-, \tag{42}$$

term reflects the additional effect of an energy-capacity right, which is that it requires a minimum SOC of the storage device between the injection and withdrawal hours.

Our next main result shows that the storage-device owner earns non-negative revenues from the allocation of storage-capacity rights. Moreover, the net revenues earned by the storage-device owner equals its imputed marginal value.

Proposition 2: Suppose $\bar{q}^c$, $\bar{q}^d$, $\bar{q}^e$, $\bar{s}$, $\bar{\lambda}$, $\bar{\sigma}^-$, $\bar{\sigma}^+$, $\bar{\gamma}^-$, $\bar{\gamma}^+$, $\bar{\mu}^{c,-}$, $\bar{\mu}^{c,+}$, $\bar{\mu}^{d,-}$, $\bar{\mu}^{d,+}$, $\bar{\mu}^{e,-}$, and $\bar{\mu}^{e,+}$ satisfy KKT conditions (12)–(26) and that the rules proposed in Proposition 1 are used to price the storage-capacity rights allocated. Then the storage-capacity auction raises:

$$\sum_{t=1}^{T} H \cdot \bar{R} \cdot \sigma_t^+ + \sum_{t=1}^{T} \bar{R} \cdot (\gamma_t^- + \gamma_t^+), \tag{43}$$

in net revenues, which are non-negative.

Proof: According to the pricing rules proposed in Proposition 1, the storage-device owner collects from rights holders:

$$\lambda_t + (\gamma_t^- - \gamma_t^+), \tag{44}$$

per MW of hour-t power-capacity discharging rights allocated and:

$$-\eta^c \lambda_t + \lambda_{t'} + \sum_{\tau=t}^{t'-1} \sigma_\tau^- - \eta^c \cdot (\gamma_t^- - \gamma_t^+) + (\gamma_{t'}^- - \gamma_{t'}^+), \tag{45}$$

per MW of energy-capacity rights with an hour t injection and hour t' withdrawal allocated. It also pays to rights holders:

$$\eta^c \lambda_t + \eta^c \cdot (\gamma_t^- - \gamma_t^+), \tag{46}$$

per MW of hour-t power-capacity charging rights allocated. Thus, the storage-device owner collects, in net:

$$\begin{aligned}&\sum_{t=1}^{T} \sum_{n \in N_t} \left[(\lambda_t + \gamma_t^- - \gamma_t^+) q_{t,n}^d - \eta^c \cdot (\lambda_t + \gamma_t^- - \gamma_t^+) q_{t,n}^c \right] \\ &\quad + \sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \Bigg(-\eta^c \lambda_t + \lambda_{t'} + \sum_{\tau=t}^{t'-1} \sigma_\tau^- \\ &\qquad - \eta^c \cdot (\gamma_t^- - \gamma_t^+) + (\gamma_{t'}^- - \gamma_{t'}^+) \Bigg) q_{t,t',m}^e, \end{aligned} \tag{47}$$

in revenues from the rights allocated. Substituting KKT conditions (12)–(14) into (47) gives:

$$\begin{aligned}&\sum_{t=1}^{T} \sum_{n \in N_t} (\pi_{t,n}^d q_{t,n}^d - \pi_{t,n}^c q_{t,n}^c) \\ &\quad + \sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \pi_{t,t',m}^e q_{t,t',m}^e \\ &\quad + \sum_{t=1}^{T} \sum_{n \in N_t} \left[(\mu_{t,n}^{d,-} - \mu_{t,n}^{d,+}) q_{t,n}^d + (\mu_{t,n}^{c,-} - \mu_{t,n}^{c,+}) q_{t,n}^c \right] \\ &\quad + \sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} (\mu_{t,t',m}^{e,-} - \mu_{t,t',m}^{e,+}) q_{t,t',m}^e. \end{aligned} \tag{48}$$

Substituting complementary slackness conditions (21)–(26), (23), and (25) into (48) gives:

$$\begin{aligned}&\sum_{t=1}^{T} \sum_{n \in N_t} (\pi_{t,n}^d q_{t,n}^d - \pi_{t,n}^c q_{t,n}^c) \\ &\quad + \sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \pi_{t,t',m}^e q_{t,t',m}^e \\ &\quad - \sum_{t=1}^{T} \sum_{n \in N_t} (\mu_{t,n}^{d,+} Q_{t,n}^d + \mu_{t,n}^{c,+} Q_{t,n}^c) \\ &\quad - \sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \mu_{t,t',m}^{e,+} Q_{t,t',m}^e. \end{aligned} \tag{49}$$

Because the storage-auction model is a linear optimization problem, the strong duality theorem gives:

$$\begin{aligned}&\sum_{t=1}^{T} H \cdot \bar{R} \cdot \sigma_t^+ + \sum_{t=1}^{T} \bar{R} \cdot (\gamma_t^- + \gamma_t^+) = \\ &\quad \sum_{t=1}^{T} \sum_{n \in N_t} (\pi_{t,n}^d q_{t,n}^d - \pi_{t,n}^c q_{t,n}^c) \\ &\quad + \sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} \pi_{t,t',m}^e q_{t,t',m}^e \\ &\quad - \sum_{t=1}^{T} \sum_{n \in N_t} (Q_{t,n}^c \mu_{t,n}^{c,+} + Q_{t,n}^d \mu_{t,n}^{d,+}) \\ &\quad - \sum_{t=1}^{T} \sum_{t'=t+1}^{T} \sum_{m \in M_{t,t'}} Q_{t,t',m}^e \mu_{t,t',m}^{e,+}. \end{aligned} \tag{50}$$

Combining this strong-duality equality with (49) implies that the storage-device owner collects:

$$\sum_{t=1}^{T} H \cdot \bar{R} \cdot \sigma_t^+ + \sum_{t=1}^{T} \bar{R} \cdot (\gamma_t^- + \gamma_t^+), \tag{51}$$

in net revenues from the capacity-rights allocation. Nonnegativity follows because by assumption H and $\bar{R}$ are positive and the Lagrange multipliers, σ_t^+, γ_t^-, and γ_t^+, are all nonnegative for all t. ■

Proposition 2 shows that the net revenues earned from the capacity-rights allocation can be broken into two terms, which can be interpreted as measuring the marginal value of the storage device. The second term:

$$\sum_{t=1}^{T} \bar{R} \cdot (\gamma_t^- + \gamma_t^+), \tag{52}$$

measures the imputed value of the power capacity of the storage device. If the optimal capacity-rights allocation results in any of power-capacity constraints (5) binding, the corresponding Lagrange multipliers measure the marginal value of adding power capacity to the storage device. The products of $\bar{R}$ and those corresponding Lagrange multipliers measure the imputed marginal value of the existing power capacity of the storage device. The first revenue term:

$$\sum_{t=1}^{T} H \cdot \bar{R} \cdot \sigma_t^+, \tag{53}$$

can be interpreted analogously. If the capacity-rights allocation exhausts the energy capacity of the storage device, the Lagrange multipliers corresponding to the binding energy-capacity constraints measure the marginal value of adding energy capacity to the storage device. The products of these Lagrange multipliers and $H \cdot \bar{R}$ measure the imputed marginal value of the existing energy capacity of the storage device.

IV. Numerical Example

We now demonstrate our proposed storage-capacity auction through two numerical examples. Both examples assume a distributed battery energy storage system with $\bar{R} = 1$, $\eta^c = 0.8$, $\eta^s = 1$, and $T = 24$. The first example assumes that the third parties wish to use the battery solely for energy arbitrage. We then consider a case in which an additional third-party wishes to use the storage for backup energy.

A. Arbitrage-Only Example

We begin with a setting in which third parties wish to use the storage solely for energy arbitrage. The third parties must compete with one another (through their bids) for power-capacity charging rights during hours when energy prices are low and power-capacity discharging rights when prices are high.

1) Data: Fig. 1 shows and Table I lists forecasted day-ahead energy prices. The third parties submit bids for power-capacity charging rights in hours 1–4 and 10–15, when prices are relatively low. We assume that in each hour a bid for 0.5 MW of power-capacity charging rights is submitted at the forecasted energy price for that hour. Bids are submitted in each hour for an additional 0.2 MW at prices 10%, 30%, and 60% higher than the forecasted energy price, meaning that bids for a total of 1.1 MW of power-capacity charging rights are submitted in each hour.

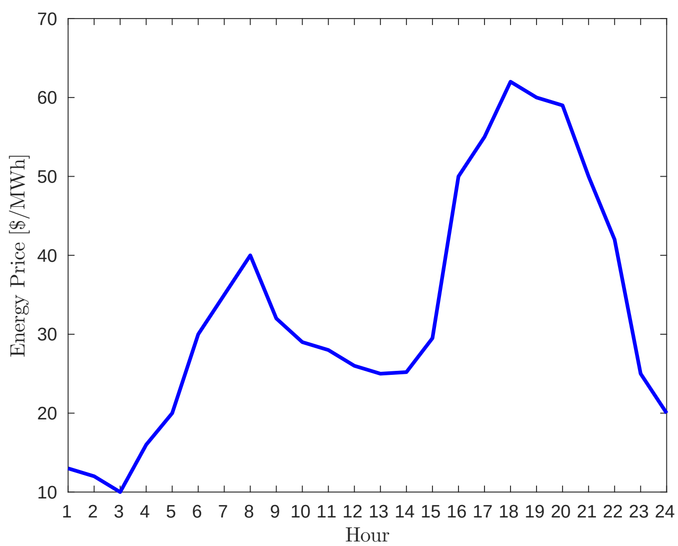

Fig. 1. Forecasted day-ahead energy prices.

TABLE I
FORECASTED DAY-AHEAD ENERGY PRICES [$/MWH]

Hour	Price	Hour	Price	Hour	Price
1	13	9	32	17	55
2	12	10	29	18	62
3	10	11	28	19	60
4	16	12	26	20	59
5	20	13	25	21	50
6	30	14	25	22	42
7	35	15	29	23	25
8	40	16	50	24	20

Third parties also submit bids for power-capacity discharging rights in hours 6–9 and 16–24. These bids are symmetrical to the power-capacity charging rights bids. A bid for 0.5 MW is submitted at the forecasted energy price in each hour. Additional bids for 0.2 MW each are submitted at prices 10%, 30%, and 60% lower than the forecasted energy price.

2) Results: We examine cases in which H takes on values between 1 and 4. Because of the double-peak in the price pattern (and the resulting bids for power-capacity charging and discharging rights) the storage-rights allocation follows a similar pattern with charging rights allocated in the early morning and midday and discharging rights allocated in the late morning and late afternoon/evening.

Table II summarizes the results of the storage-capacity auction in the cases examined. It lists the MW of charging and discharging rights allocated, the prices at which they clear (following the pricing rules outlined in Proposition 1) and the margin earned by the bidders. This margin is defined as the difference between what each storage-right owner values the right at (based on the value of π specified in the bid) and the price paid for the right. The final column of Table II reports the total revenues earned by the storage owner through the auction, which is the quantity shown in Proposition 2 to be:

$$\sum_{t=1}^{T} H \cdot \bar{R} \cdot \sigma_t^+ + \sum_{t=1}^{T} \bar{R} \cdot (\gamma_t^- + \gamma_t^+). \tag{54}$$

TABLE II
RESULTS OF STORAGE-CAPACITY AUCTION IN ARBITRAGE-ONLY EXAMPLE

	Charging Rights			Discharging Rights			
H	MW	Avg. Price $/MW	Bid. Marg. $	MW	Avg. Price $/MW	Bid. Marg. $	Auct. Rev.
1	2.50	19.50	3.3	2.00	47.00	4.7	45.3
2	4.00	20.31	12.2	3.20	47.27	11.6	70.0
3	5.25	21.57	23.3	4.20	45.54	24.0	78.0
4	6.50	28.00	61.0	5.20	42.69	42.2	40.0

Table II reports some expected results of this analysis. First, as H increases the differences between the prices at which the charging and discharging rights clear get smaller. This is because when H is small (take, as an example, the case of $H = 1$), the storage-capacity auction allocates charging rights to the smallest bids in hours 2–3 and 12–14 and discharging rights to the highest bids in hours 7–8 and 18–19. As H gets larger, the auction can allocate charging and discharging rights to higher and lower bids, respectively. In the case of $H = 4$, charging rights are allocated in hours 1–4 and 11–14 and discharging rights are allocated in hours 7–8 and 16–21.

The allocation of power-capacity rights given by the model also follows the 'connecting' logic discussed in Section III-A. In the case of $H = 2$, there is a $31.50/MW bid for a discharging power-capacity right that is not accepted. The reason that this bid is not accepted is that the highest bid for a charging power-capacity that this discharging right could be 'connected' with is $27.50. When the $\eta^c = 0.8$ efficiency of the storage device is taken into account, accepting these two power-capacity rights would be uneconomic.

The second finding in Table II is that the value of the storage device, as revealed by the auction revenues, is increasing in H for small values of H but then decreases. When H is small, additional storage capacity is valuable, because it allows more valuable bids for power-capacity rights to clear the auction. As H increases, however, more bids that are submitted for charging and discharging rights (with smaller margins) clear the auction and additional capacity is less valuable.

The third finding is that the auction and, in particular, the pricing rule suggested in Propositions 1 and 2 result in the total value of the storage device being divided between the device owner and the bidders who are allocated storage-capacity rights. If the storage device is to participate directly in the energy market, as opposed to indirectly through the allocation of storage-capacity rights, the profit that would be earned by the storage device would exactly equal the sum of the auction revenue and margin earned by the bidders, which are reported in Table II.

The storage-capacity auction results in the storage owner earning the marginal value of the device through the revenues earned from allocating storage-capacity rights. Note that the marginal value of storage capacity is not necessarily equal to the total value of a storage device. One consequence of this finding is that if a storage device is ultimately to be used solely for providing services that are priced in the market, the storage owner would earn higher profit from directly participating in the wholesale market, as opposed to participating indirectly by allocating storage-capacity rights.

B. Backup-Energy Example

We now examine a case in which another party would like to use the storage to provide backup energy to customers on the distribution circuit, in the event of an outage event. More specifically, this bidder would like to charge between 1.0 MW and 1.5 MW of energy into the battery in hour 5, which it will discharge in hour 19. Moreover, it would like the energy that is charged in hour 5 to remain stored in the battery between hours 5 and 19. Thus, the battery would be providing backup energy between hours 5 and 19.

We begin by stressing that this use of storage cannot be accomplished using power-capacity rights alone. The reason is that power-capacity rights only guarantee an injection or withdrawal of energy to or from the storage device in specific hours. They do not guarantee that the injected energy remains in the storage device between the charging and discharging hours. Fig. 2 demonstrates this by showing the values of s_t given by the power-capacity rights allocated in the arbitrage-only case when $H = 2$. The important result to note is that the power-capacity rights allocated charge the battery in the morning and discharge it in the evening. However, because of other power-capacity rights allocated midday, the state of charge of the battery drops below the desired 1.0 MW threshold in hours 8–11. Thus, the battery cannot provide the desired backup energy during this window of time, regardless of how many power-capacity rights the party purchases.

The party wishing to use the battery for backup energy can do so by purchasing energy-capacity rights with an injection of energy in hour 5 and a withdrawal in hour 19. We assume that this party submits a bid for 1.0 MW of such an energy-capacity right at a price of $\$1000$/MW and for an additional 0.5 MW at a price of $\$500$/MW. We assume that these bids reflect the expected value of lost load to end customers. When these bids are submitted, 1.0 MW of energy-capacity rights are allocated. Indeed, the right is allocated for any bid above $\$39.90$/MW, and this threshold value can be determined through numerical testing or analytically. Fig. 2 shows the resulting values of s_t over the course of the day when the energy-capacity bid is included in the auction. We see that as a result of the energy-capacity bid being accepted, the state of charge of the battery remains above the desired 1 MWh between hours 5 and 19. The energy-capacity right only restricts the battery state of charge between these hours, however, as we see that s_t returns to 0 MWh in hours 20–24.

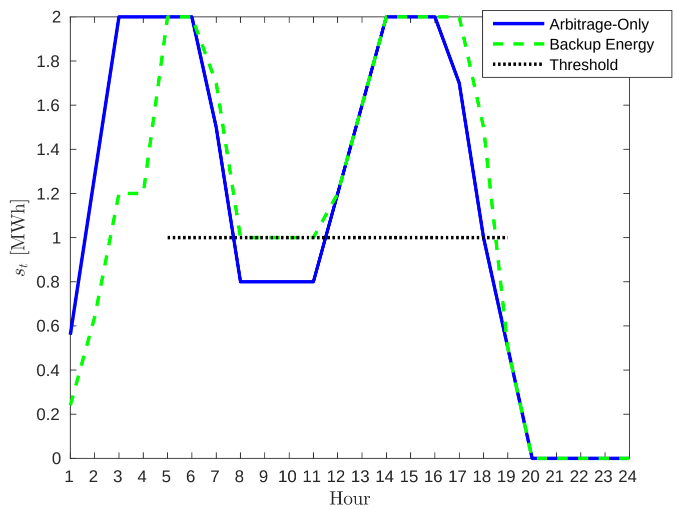

Fig. 2. s_t in the Arbitrage-Only and Backup-Energy examples with $H = 2$.

The energy-capacity bid affects the allocation of power-capacity rights as well. Only 2 MW of power-capacity discharging rights are allocated, meaning that less storage capacity is used for energy arbitrage. Moreover, the revenues raised from allocating power-capacity rights for energy arbitrage decreases from $\$70.00$ (*cf.* Table II) to $\$38.80$. However, the auction raises an additional $\$499.20$ from the energy-capacity right sold, meaning total auction revenues increase to $\$538.80$.

This $\$538.80$ raised through allocating the energy-capacity right is also greater than the revenue that the storage device could earn from directly participating in the wholesale market for energy arbitrage only, which is $\$93.84$ (*cf.* the bidder-margin and auction-revenue values for the case of $H = 2$ reported in Table II). This, thus, demonstrates the benefits of the proposed storage-capacity auction to the storage-device owner. The auction allows the owner to capture the value of services that are priced in the wholesale market and services that are not. Note, however, that the revenues earned through the allocation of storage-capacity rights is sensitive to problem data. For instance, if the bid for the energy-capacity is priced at $\$39.90$, the allocation of storage-capacity rights only raises $\$72.50$ in revenues, which is greater than the revenues earned in the arbitrage-only case (*cf.* Table II) but less than what could be earned from directly participating in the wholesale market for energy arbitrage only. It also bears mentioning that the energy-capacity right, which is worth $\$1000$ in expectation is obtained by the party for $499.20. This means that customer reliability is increased (with a commensurate benefit of $1000) at a cost of $499.20.

The costs borne by the third parties of obtaining the power- and energy-capacity rights would be recovered differently. Because the power-capacity rights are being used to arbitrage hourly price differences, the $70.00 spent on those rights would be recovered from the wholesale energy market. The energy-capacity rights, conversely, are being used to provide backup energy to end customers (they may, for instance, be purchased by the local distribution utility). Because these rights are being used to provide a service that is not competitively priced in the wholesale market, the $499.20 spent on these rights would be recovered through the ratebase. The utility would presumably demonstrate to the regulatory authority that the energy-capacity rights are a prudent means of increasing system reliability for the end customers being served by the 1 MW of energy-capacity rights.

V. Discussion and Concluding Remarks

Our proposal to auction storage-capacity rights surmounts the cost-recovery problem that energy storage faces with today's hybrid regulatory design. This cost-recovery issue stems from the fact that some storage assets can provide services that are competitively priced and other services that are not. Such a storage asset would not be able to capture all of the value that it provides through either of market- or rate-based cost-recovery alone.

Our proposal works by auctioning storage-capacity rights to third parties that use those rights for services that are either competitively priced or unpriced. If a third party uses its rights to provide a competitively priced service, it recovers the cost of its rights through the competitive market. Otherwise, if a third party uses its rights to provide an unpriced service, the cost of its rights can be recovered through the appropriate regulatory channels. Thus, from the asset owner's perspective, the benefits that the storage asset provide are disentangled from the regulatory treatment of those benefits.

Section IV-B discusses a specific case of storage-capacity rights being used for two different purposes (energy arbitrage and backup energy) and how the costs of obtaining the storage-capacity rights needed for the different applications would be recovered through market-based or regulatory channels. It should be stressed that the cost-recovery mechanism used *does not* depend on the type of storage-capacity right obtained. Rather, the cost-recovery mechanism employed depends on what the storage-capacity rights obtained are used for. For instance, one would rely on energy-capacity rights if using storage for frequency regulation. The cost of these rights would be recovered through market prices, unlike the energy-capacity rights obtained to provide backup energy in the example in Section IV-B.

The proposed auction allows third parties to use storage assets for different purposes that are of interest to them. A distribution utility could use storage to increase service reliability for its customers. A load-serving entity could use storage to self-supply frequency regulation. A wind generator could store excess wind production overnight and sell the energy midday when prices are higher.

The proposed auction design has two attractive features. First, the capacity-allocation model generates prices that are intuitively clear and transparent. Moreover, these prices are equilibrium-supporting in the sense that each storage-right owner would want to follow the injections and withdrawals of energy specified by the allocation. Secondly, the net revenues earned by the storage-device owner from allocating the storage-capacity rights exactly equal the imputed marginal value of the storage device. Thus, the storage owner is able to extract the market value of its device through the auction. Our numerical example does show that if the storage asset is ultimately used exclusively to provide priced or unpriced services *only*, having the asset directly provide those services as opposed to doing so indirectly through the allocation of storage-capacity rights allows the asset to retain more revenue.

Importantly, our proposed auction design is able to capture the value of services that are competitively priced and unpriced without introducing subsidies that could harm price formation in the market. This feature is important as energy storage is increasingly being deployed through regulatory mandates. For instance, the California Public Utilities Commission recently mandated that the three investor-owned utilities in California invest in energy storage at the distribution level. The costs of these assets may ultimately be recovered through the ratebase. If so, allowing them to participate in the CAISO markets could undermine the price-formation process and the efficiency of the wholesale market. Our proposal offers an alternative cost-recovery scheme that could overcome this issue and allow for the full value of the assets to be captured.

As discussed in Section III, the types of storage-capacity rights defined in our model are not exhaustive and other types of rights could be defined. Our model and the examples in Section IV assume that the storage rights are obligations, as opposed to options. This is needed in our model to ensure that all of the rights are simultaneously feasible. If, as an example, the holder of a power-capacity charging right does not charge energy into the storage device, the storage device may not be able to fulfill a power-capacity discharging right in a subsequent hour. Treating storage-capacity rights as obligations is no different than the treatment of generation or load bids that clear in a day-ahead or real-time energy market. Bids in day-ahead and real-time markets are treated as obligations to ensure that load is balanced and power flows are feasible. Day-ahead and real-time market rules typically include deviation penalties to ensure that bids that clear are physically delivered. Similarly, deviation penalties may be needed to ensure that storage-capacity rights are exercised.

One capacity right that may be beneficial for certain storage applications is an energy-capacity right that is an option. To see this, consider the party wishing to use an energy-capacity right to provide backup energy between hours 5 and 19 in the example in Section IV-B. The right that this party holds requires 1.0 MW to be injected in hour 5, which remains in storage until hour 19 when it must be discharged. If an outage is to occur in hour 13, this party would have to purchase an additional power-capacity discharging right on the spot market (which is priced at $\$32.50$/MW in the example in Section IV-B) to extract the 1.0 MW before hour 19. In this case, the $\$499.20$ spent purchasing the energy-capacity right is akin to the payment made to a generator to provide spinning or nonspinning reserves, independent of whether the reserves are called in real-time. The additional $\$32.50$ spent purchasing the power-capacity right in the event of a system outage is akin to the supplemental energy payment made to a generator if its spinning or nonspinning reserves are called in real-time.

An alternate approach would be to define an energy-capacity option product. Such a product would allow the party to withdraw the energy at any time between the charging and discharging hours. Such an option would change power-capacity constraints (5) in the storage-auction model because they would have to account for the possibility of the option being exercised at any point between the charging and discharging hours. This would, in turn, change the optimal pricing rule to include the γ_t^- and γ_t^+ Lagrange multipliers for all hours between the charging and discharging hours. Another storage right that may be beneficial is a power-capacity right that consists of a coupled injection and withdrawal of energy. We do not model such rights for sake of brevity. However, the model can be easily extended to include these and others. This issue of storage-capacity options raises an important future research question, which is extending the storage-auction model to explicitly capture uncertainties. A stochastic programming framework could generate prices that capture the inherent uncertainty in when different storage-capacity options may be exercised. Of course, such a model supposes that the auctioneer or another entity could model scenarios around such events, which may be difficult to do in practice.

There are two important implementation issues that our model is agnostic to: the timing of the storage-capacity auction and who operates it. Different storage uses may require different lead times for the auction (*e.g.*, months-ahead for capacity deferral versus hour-ahead for some AS). Thus, a sequence of auctions may help ensure that a storage asset is efficiently used. A sequence of auctions could also allow benefit bidders and the auctioneer by allowing the rights allocated to be reconfigured. Such reconfiguration auctions are common in the electricity industry, *e.g.*, hour-ahead and real-time energy and AS markets, incremental capacity markets, and reconfiguration auctions for transmission rights. So long as the reconfigured capacity-right allocation is feasible relative to the outstanding rights, the efficiency properties proven in Propositions 1 and 2 hold.

Our model is also agnostic to who operates the storage-capacity auction. An interesting consideration is that an independent system operator (ISO) may be able to operate the auction without threatening its market independence. This is because our proposed auction allocates storage-capacity rights on the basis of bids submitted by independent third parties. Thus, the storage-capacity rights are allocated in a manner that is analogous to an ISO allocating transmission capacity or dispatch among generators in its energy market or financial transmission rights. The auctioneer's role in our proposal is different than what was proposed in the LEAPS case, which was to have the CAISO operate the storage plant to minimize congestion rents. The proposal in the LEAPS case would have seen the CAISO directly affecting the price-formation process. Moreover, the CAISO would have effectively acted as a monopsonist with respect to congestion costs in operating the LEAPS plant.

A benefit of having the ISO operate the storage-capacity auction is that it could be coordinated with energy and AS markets. A third party that bids for power-capacity rights for energy arbitrage is exposed to some price risk between the two markets. Combining and coordinating them could mitigate such risks.

Although the ISO may be able to operate the auction without threatening its independence, it may not be an ideal auctioneer. One reason is that distributed energy storage may be a major use case for our proposed auction. By its nature, distributed energy storage is deployed at points in the power system that are not typically included in an ISO's operations, planning, and models. Thus, a distribution system operator (DSO) or the incumbent distribution utility may be better suited to operate the auction. An entity akin to a DSO could further serve as the auctioneer for multiple distributed energy storage devices and could allocate their capacity in an aggregated fashion. This may lower transaction costs relative to having capacity rights for each individual storage device allocated in a separate auction.

A DSO or similar type of aggregator could also coordinate bidding for storage assets that are electrically close to each other in terms of having minimal transmission constraints between them. Our model does not capture transmission constraints. Instead, we assume that all of the bidders are interested in obtaining storage-capacity rights where the device is physically located in the network. In practice, a particular storage device may only see a subset of potential bidders interested in obtaining storage-capacity rights from it, depending on its physical location in the network.

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