Energy Storage: Market Power and Social Welfare

Jesus E. Contereras-Ocaña, Yishen Wang, Miguel A. Ortega-Vazquez, and Baosen Zhang
University of Washington Electrical Engineering
Emails: {jcontrer, ywang11, maov, zhangbao}@uw.edu

***Abstract*—As energy storage systems (ESSs) become economically competitive, it is natural to expect significant increases in deployments in the near future. Consequently, these systems will form a nontrivial part of the energy market and may exhibit strategic actions as ESS owners strive to maximize their profits. In this work we study the impact of *strategic bidding of ESSs* on the rest of the power system players and propose a *non-uniform pricing scheme* designed to mitigate adverse impacts. We show that while strategic bids increase the ESS's profits, it has negative impacts on the social welfare and mixed impacts on other players. We also show that the proposed pricing scheme incentivizes the ESSs to behave in a socially optimal manner and allows for profit regulation and welfare distribution among the players.**

***Index Terms*—Energy storage, market power, social welfare, strategic bidding, pricing.**

I. Introduction

Energy storage systems (ESSs) have the potential of benefiting the power system in a number of ways: *e.g.*, increasing the hosting capacity for renewable energy sources, increasing the reliability and efficiency of the system, enabling energy arbitrage and provide ancillary services among others [1]. In deregulated power systems, however, energy storage owners strive to maximize their profits rather than the system welfare [2].

Regulators are pushing for ambitious levels of energy storage in power grids which can potentially lead to large ESSs. For instance, the California Public Utilities Commission set a target of 1.3 GW of energy storage capacity by 2020 [3] and a single 100 MW/ 400 MWh energy storage project in Los Angeles, CA is expected to be completed by 2021 [4]. Owners of these systems control large amounts of flexible capacity and may be able to exercise *market power* by bidding strategically. Exercising market power reduces the benefit that ESSs deliver to the grid.

This paper attempts to answer a few basic questions: *i)* What is the social cost of strategic bidding by ESSs? *ii)* Can we induce the ESS to behave in a socially desirable manner? If so, who are the winners and who are the losers in the system? Could we design a mechanism in which everyone benefits by the ESS behaving in a socially optimal way?

To address *i)*, we define the *1)* socially optimal operation of the ESS and *2)* the strategic bidding model of the ESS. Then, we look at how each participant fares in each of these two models. To address *ii)* we present a novel non-uniform pricing scheme that can be used by the system operator (SO) in lieu of the classical marginal pricing in order to incentivize ESSs to behave in a socially optimal manner. This pricing scheme has the properties of: being consistent with rational behavior of the ESS (*i.e.*, it is in the ESS's best interest to behave in a socially optimal manner) and allowing for the regulation of the ESS's profit. Then we show that it is possible to design a scheme of side-payments that leave every participant better-off compared to the case where the ESS bids strategically.

A. Literature Review

The exercise of market power is a major concern among regulators and SOs [5]. However, the large majority of works deal with the market power of generating units (*e.g.*, see [6], [7]). Since large scale penetration of energy storage is a relatively new phenomenon, market power by ESSs is currently a scarcely researched problem.

Some relevant work on the issue of market power by ESSs is found in [8], [9]. However, the problem is seen from the perspective of the ESS's profit or technical impacts of the ESS's market power on the power system, (*e.g.*, system congestion or the ability of the ESS to aid renewable energy integration). The social welfare aspect is not fully addressed. Moreover, to the best of our knowledge a market power mitigation mechanism for ESSs is not yet available.

B. Contributions

The contributions of this work are as follows: *i)* an in-depth analysis of the social impacts of strategic bidding by an ESS performing spatio-temporal energy arbitrage, *ii)* a non-uniform pricing mechanism that incentivizes a profit-seeking ESS to behave in a socially optimal fashion and allows for the regulation of its profit.

C. Organization of the paper

Section II describes the power system and ESS models used throughout the paper. Section III describes the profit-maximizing bidding strategy of the ESS. Section IV defines the concept of social welfare and how it is allocated among the system participants. It also describes the ideal case where rather than bidding strategically, the ESS reports its true cost for the SO to maximize the social welfare. Section V introduces the proposed pricing scheme. Section VI provides numerical results to illustrate our claims and VII concludes the paper.

II. Power system and energy storage models

We consider two major entities: *i)* the SO, who is responsible of maximizing social welfare while observing the power system constraints; and *ii)* the ESS operator who strives to maximize profits derived from energy arbitrage.

A. Power system

To focus on the problem of strategic behavior, we assume a setting where the SO has perfect forecasts of demand, generation, and transmission availability. Furthermore, the network is modeled using DC power flows. Investigating the impact of forecast uncertainties and AC power flows are important future directions.

The SO must ensure that four major technical limits are observed. The first one is related to each generator: the power output of each generator, $p_{i,t}^G$, must be within the operating limits. $\underline{P}_i$ and $\overline{P}_i$, as shown by constraints (1a). The rest of the technical limits concern the entire power system: the power produced must equal the demand (1b); each line flow, $f_{l,t}$ must be within limits, $-\bar{F}_l$ and $\bar{F}_l$, at all times as expressed by equations (1c); and the bus voltage angles, $\theta_{b,t}$ must be within stability limits, as expressed by equations (1d). The following equations summarize these constraints:

$$\underline{P}_i \leq p_{i,t}^G \leq \overline{P}_i,\ \forall\, i \in I,\ \forall\, t \in T \tag{1a}$$

$$p_{b,t}^{\text{bus}} + q_{b,t}^{\text{bus}} = d_{b,t} + \sum_{l \in L} m_{l,b}^L f_{l,t},\ \forall\, b \in B, \forall\, t \in T \tag{1b}$$

$$-\bar{F}_l \leq f_{l,t} = \frac{\theta_{s(l),t} - \theta_{e(l),t}}{X_l} \leq \bar{F}_l,\ \forall\, l \in L, \forall\, t \in T \tag{1c}$$

$$-\pi \leq \theta_{b,t} \leq \pi,\ \forall\, b \in B,\ \forall\, t \in T \tag{1d}$$

$$\theta_{b,t} = 0,\ b = \text{ref},\ \forall\, t \in T \tag{1e}$$

where the set of all generators, buses, energy storage units, lines, and time periods are denoted by I, B, H, L, and T, respectively.

The power injected (when positive) or extracted (when negative) at time t by the storage units connected to bus b is denoted by $q_{b,t}^{\text{bus}} = \sum_{h \in H} m_{h,b}^{ES}(q_{h,t}^d - q_{h,t}^c)$ where rate of charge and discharge of storage unit h at time t are denoted by $q_{h,t}^c$ and $q_{h,t}^d$, respectively. The power injected at time t by generators connected to bus b is denoted by $p_{b,t}^{\text{bus}} = \sum_{i \in I} m_{i,b}^G p_{i,t}^G$. The parameters $m_{i,b}^G$ and $m_{h,b}^{ES}$ are elements of the generator and ESS incidence matrices, respectively. The constant $m_{i,b}^G / m_{h,b}^{ES}$ is 1 if generator i/ storage unit h is connected to bus b and 0 otherwise. The load at bus b at time t is denoted by $d_{b,t}$. The constant $m_{l,b}^L$ is an element of the line map matrix and its value is 1 if line l starts at node b, -1 is it ends at node b, and 0 otherwise. The power flow on a line from bus $s(l)$ to bus $e(l)$ is a function of the difference between the voltage angle at bus $s(l)$ and the voltage angle at bus $e(l)$, and the line reactance X_l [10]. Finally, the voltage angle at the reference bus is set by constraints (1e).

Constraints (1a)-(1e) define the feasible operating region of the power system. Now we characterize the technical limits and operating region of the ESS.

B. Energy storage system

In this paper we focus on when the ESS is used for *energy arbitrage*. Energy arbitrage is an important revenue stream for an energy storage system and can help justify investment costs [1]. The ESS operator owns and operates a set of storage units distributed throughout the grid. The rate of charge, $q_{h,t}^c$, and discharge, $q_{h,t}^d$, must be within bounds, $\overline{q}_h^c$ and $\overline{q}_h^d$, as expressed by constraints (2a) and (2b), respectively. The amount of stored energy, $SoC_{h,t}$, must be within bounds, $\underline{SoC}_h$ and $\overline{SoC}_h$, at all times as expressed by constraints (2c). Constraints (2d) describe the state-of-charge (SOC) dynamics. The SOC of storage unit h at time t, $SoC_{h,t}$, is equals its SOC at $t-1$ plus the energy inflows, $\Delta q_{h,t-1}^c \, \eta_h^c$ and outflows $\Delta q_{h,t-1}^d / \eta_h^d$ at $t-1$. The length of each time step is denoted by Δ. The charging and discharging efficiencies are characterized by $\eta_h^c \in (0,1]$ and $\eta_h^d \in (0,1]$, respectively. Additionally, the initial energy stored by each storage unit must equal their final energy stored as expressed by constraint (2e). This ensures that energy sold during the time horizon is paid for during the time horizon. The following equations describe technical limits of the ESS:

$$0 \leq q_{h,t}^c \leq \overline{q}_h^c,\ \forall h \in H,\ \forall t\ \in T \tag{2a}$$

$$0 \leq q_{h,t}^d \leq \overline{q}_h^d,\ \forall h \in H,\ \forall t\ \in T \tag{2b}$$

$$\underline{SoC}_h \leq SoC_{h,t} \leq \overline{SoC}_h,\ \forall h \in H,\ \forall t\ \in T \tag{2c}$$

$$SoC_{h,t} = SoC_{h,t-1} + \Delta q_{h,t-1}^c \, \eta_h^c - \Delta q_{h,t-1}^d / \eta_h^d,\ \forall h \in H,\ \forall t \in \mathcal{T} \tag{2d}$$

$$SoC_{h,|T|} = SoC_{h,0},\ \forall h \in H. \tag{2e}$$

Note that under the assumptions of non-negative prices and due to non-ideal efficiencies, simultaneous charging and discharging is never optimal. If we consider the expected future value of energy, (2e) could be relaxed to increase operating flexibility of the ESS [11]. Following the approach in [11] might be of particular importance if the horizon that follows $|T|$ differs significantly from T. For simplicity, we ignore future prices and use constraints (2e). We are confident that our qualitative results hold when (2e) is relaxed.

Finally, it is known that charging/discharging affects the useful lifetime of chemistry-based ESSs [12]. The cost of utilizing the ESS is characterized by the linear cost function

$$C^{ES} = \sum_{h \in H,\ t \in T} \alpha_h \Delta(q_{h,t}^d + q_{h,t}^c).$$

where the coefficient α_h is related to the degradation and operation costs of unit h.

The aforementioned constraints characterize the feasible operating region of the ESS. The following section introduces the problem that the ESS solves to maximize its profit. Rather than simply bidding in accordance to its true cost/utility, the ESS strategically determines its bids into the market.

III. Bidding strategy

In this section, we introduce the market setting in which the ESS operates and formulates its profit maximization problem. If the ESS is large enough, its bids might significantly affect the market clearing prices. In this case, the ESS's best strategy is to treat the market clearing prices as endogenous to its profit maximization problem. The problem of ESS profit maximization under endogenous prices is typically modeled as a *bilevel optimization* problem where the upper level objective is to maximize the ESS's profit subject to the market clearing process in the lower level [9], [13], [14].

A. Price-quantity bids from the ESS

We consider a market setting that allows the ESS to submit price-quantity demand bids (for energy purchases) and price-quantity supply bids (for energy sells) as in [13]. For each storage unit and time period, it bids $\Delta q_{h,t}^{\text{supply}}$ units of energy (for injection) at the price $\rho_{h,t}^{\text{supply}}$ or bids for $\Delta q_{h,t}^{\text{demand}}$ units of energy (for extraction) at the price $\rho_{h,t}^{\text{demand}}$. The objective of the ESS operator is to formulate supply and demand bids such that its profit, given by

$$J^{ESS}(\boldsymbol{y},\boldsymbol{\lambda})=\sum_{b\in B,\, t\in T}\lambda_{b,t}\Delta q^{\text{bus}}_{b,t}-C^{ES},$$

is maximized. The price paid to (when selling) or paid for (when buying) by the ESS operator for withdrawals/injection at bus b is the LMP, $\lambda_{b,t}$. The ESS-exclusive variables are denoted by $\boldsymbol{y}=\left\{q^c_{h,t},\ q^d_{h,t},\ SoC_{h,t}, \rho^{\text{supply}}_{h,t}, \rho^{\text{demand}}_{h,t}\right\}_{h\in H, y\in T}$. The set of all LMPs is denoted by $\boldsymbol{\lambda}=\{\lambda_{b,t}\}_{b\in B, t\in T}$. The LMPs $\boldsymbol{\lambda}$ are the dual variables of the nodal power balance constraints (1b) obtained from the market clearing process.

B. Market clearing

The ESS determines its bids while assuming that the load bids its true utility and that the generators bid their true cost. The market clearing process is modeled as an optimization problem in which the SO maximizes the social welfare as revealed by the participant's bids. The SO maximizes

$$J^{SO,\text{bid}}(\boldsymbol{x},\boldsymbol{y})=\sum_{h\in H,\, t\in T}(\rho^c_{h,t}\Delta q^c_{h,t}-\rho^d_{h,t}\Delta q^d_{h,t})-\sum_{i\in I,\, t\in T}F_i(p^G_{i,t}),$$

where the function $F_i(\cdot)$ represents the piece-wise linear price-quantity bid (and true cost) of generator i. The clearing charging/discharging quantities $\Delta q^c_{h,t}/\Delta q^d_{h,t}$ should be smaller than or equal to the bid quantities $\Delta q^{\text{demand}}_{h,t}/\Delta q^{\text{supply}}_{h,t}$. It is assumed that the load price bid is high enough for all its quantity to be cleared. This last assumption allows ignoring the load's utility term in the SO's objective function.

C. Bilevel optimization model of strategic bidding

The prices paid by/for the ESS derive from the social welfare maximization problem. Thus, bidding problem of the ESS operator can be formulated as the following bilevel optimization problem:

$$\max_{\boldsymbol{x},\boldsymbol{y},\boldsymbol{\lambda}}\ J^{ESS}(\boldsymbol{y},\boldsymbol{\lambda}) \tag{3a}$$

$$\text{s.t. } \boldsymbol{y}\in Y^{ESS} \tag{3b}$$

$$\{\boldsymbol{x},\boldsymbol{\lambda}\}\in \arg\max_{\boldsymbol{x}\in X^{SO}}\ J^{SO,\text{bid}}(\boldsymbol{x},\boldsymbol{y}) \tag{3c}$$

where the power system-exclusive variables are denoted by $\boldsymbol{x}=\left\{\{p^G_{i,t}\}_{i\in I},\{f_{l,t}\}_{l\in L},\{\theta_{b,t}\}_{b\in B}\right\}_{t\in T}$. The feasible operating region of the electric network described by equations (1a)-(1e) is denoted by X^{SO}. Similarly, the feasible operating region of the ESS described by equations (2a) - (2e) is denoted by Y^{ESS}. Here, the upper-level objective, (3a), is to maximize the ESS profit subject to the ESS constraints (3b) and the market clearing process (3c). In the upper level, the ESS determines its supply/demand price-quantity bids. In the lower level, the SO schedules generation and charging/discharging of the ESS in order to maximize the social welfare.

1) Solution approach: The bilevel problem described by equations (3) is recast as a single-level optimization problem by replacing the lower level problem (3c) by its Karush-Kuhn-Tucker optimality conditions. The resulting single-level problem, however, is hard to solve as it is non-linear (the upper-level objective, J^{ESS}, is a product of variables) and non-convex (the lower-level complimentary slackness conditions are equalities and product of variables). However, the upper-level objective is linearized by invoking the strong duality theorem on the convex lower-level problem. The lower-level complimentary slackness conditions are linearized using the Fortuny-Amat and McCarl transformations. The resulting problem is a mixed-integer linear program that can be efficiently solved using commercial solvers (*e.g.*, CPLEX). Due space limitations, we skip the detailed description and refer interested readers to [2], [13].

IV. Social Welfare

In this section we define *i)* how the welfare/profits are allocated among participants and *ii)* the problem that the SO solves in the ideal case. Ideally, each participant would bid according to its true cost/utility. In this case, the market clearing process maximizes the *true* social welfare of the system. However, the ESS is not compelled to bid according to its true costs or utilities.

A. Social welfare distribution

In order to know who "wins" and who "looses" due to the ESS strategic bid, it is useful to define how the social welfare is allocated among four actors in the system: *i)* the producers and *ii)* ESS whose welfare is their profit, *iii)* the load whose welfare is the utility derived from consuming electricity minus electricity payments, and *iv)* the transmission system owner whose welfare is the transmission surplus. All in all, the system welfare is given by the following definition.

Definition 1. The social welfare, SW, of the system is equivalently defined as *i)* the sum of the welfare of the four aforementioned actors or *ii)* the benefit that the load derives from consuming electricity minus the cost of operating the power system and the ESS:

$$SW=J^G+J^{ESS}+J^D+J^{TS}=\sum_{b\in B t\in T}U\Delta d_t-\sum_{i\in I,t\in T}F_i(p^G_{i,t})-C^{ES} \tag{4}$$

where:

$$J^G=\sum_{i\in I,t\in T}[\lambda_{b(i),t}\Delta p^G_{i,t}-F_i(p^G_{i,t})],\ J^D=\sum_{b\in B,t\in T}(U-\lambda_{t,b})\Delta d_{t,b}$$

$$J^{TS}=\sum_{b\in B,t\in T}\lambda_{t,b}\Delta(d_{b,t}-q^{\text{bus}}_{b,t}-p^{\text{bus}}_{b,t}).$$

The load's benefit per MWh is denoted by U. The symbol J^D denotes the load's surplus. The producer's profit is denoted by J^G and $\lambda_{b(i),t}$, is the locational marginal price (LMP) at time t at the bus generator i is connected to. The bus that generator i is connected to is denoted by $b(i)$. The transmission surplus as defined in [15] is denoted by J^{TS}.

B. Social optimum

Ideally, the SO would operate the system by maximizing the social welfare as defined by (4) while observing all technical constraints. Then, the socially optimal operation of the system is given by the following definition.

Definition 2. The solution to the problem

$$\max_{\boldsymbol{x},\boldsymbol{y}}\ SW \tag{5a}$$

$$\text{s.t. } \{\boldsymbol{x},\boldsymbol{y}\}\in X^{SO} \tag{5b}$$

$$\boldsymbol{y}\in Y^{ESS}, \tag{5c}$$

denoted by $\boldsymbol{x}^*$ and $\boldsymbol{y}^*$, defines the socially optimal operation of the system.

V. Market power

In general, the strategic bid of the ESS does not equal the socially optimal bid. Thus, while strategic bidding maximizes the ESS's profit, it is likely to reduce the social welfare and have a net detrimental impact.

A. Market power mitigation

The goal of the SO is to operate the system such that the social welfare is maximized. However, strategic bidding by the ESS prevents the system from fully exploiting the potential benefits of the ESS. Thus, in order to induce the ESS operator to reveal its true costs, the SO may adopt the pricing scheme defined by the following theorem.

Theorem 1. A ESS operator who bids according to the solution to problem (3) behaves in a socially optimal fashion if instead of being exposed to the LMP $\boldsymbol{\lambda}$ it is exposed to the price given by:

$$\tau_{b,t}(\boldsymbol{x},\boldsymbol{y}) = -\frac{\sum_{i\in I} m^G_{i,b} F_i(p^G_{i,t}) + c_t}{q^{\text{bus}}_{b,t}}.$$

As shown in the proof, the terms c_t are a constant in the objective function of the ESS and can be set arbitrarily without affecting the solution of the optimization solved by the ESS. This means that the profit of the ESS can be regulated to an arbitrary level without affecting the short term operation of the ESS. Its important to note that the regulated profit does affect long-term decisions (*e.g.*, investment decisions).

Proof. The social welfare maximization problem described by equations (5) can be recast as

$$\max_{\boldsymbol{x},\boldsymbol{y}} SW \tag{6a}$$
$$\text{s.t. } \boldsymbol{y} \in Y^{ESS} \tag{6b}$$
$$\boldsymbol{x} \in \arg\max_{\boldsymbol{x}\in X^{SO}} SW. \tag{6c}$$

by enforcing the optimality of the set of variables $\boldsymbol{x}$ in a lower-level problem [16].

It can be shown that replacing $\boldsymbol{\lambda}$ in (3a) by $\boldsymbol{\tau} = \{\tau_{b,t}(\boldsymbol{x},\boldsymbol{y})\}_{b\in B, t\in T}$ the objective of the ESS becomes: $\max_{\boldsymbol{x},\boldsymbol{y}} SW + c^{\text{reg}}$ where $c^{\text{reg}} = \sum_{t\in T} c_t$, which is equivalent to maximizing the social welfare when the ESS bids its true cost. Thus, the objective of problem (3) (when exposed to the pricing scheme $\boldsymbol{\tau}$) is exactly aligned with the objective of social welfare maximization problem (6) plus a constant term c^{reg}. We conclude that the ESS operator bids according to the socially optimal $\boldsymbol{y}^*$.

□

B. Profit regulation

As previously stated, the term for profit regulation of the ESS, c^{reg}, can be set arbitrarily without affecting the short term operation of the ESS. The money transferred to/form the ESS via the term c^{reg}, has to come from/go to other players in the system.

The task of SOs is to maximize the social welfare. Whether the resulting welfare allocation is "fair" or not is typically a more subtle question to answer, partly because it is difficult to define a rigorous notion of fairness. Here we assume that this side payments can be arranged in a way that advances the objectives of the SO/regulators such as: favoring certain technologies (*e.g.*, clean energy), funding uplift payments, among others.

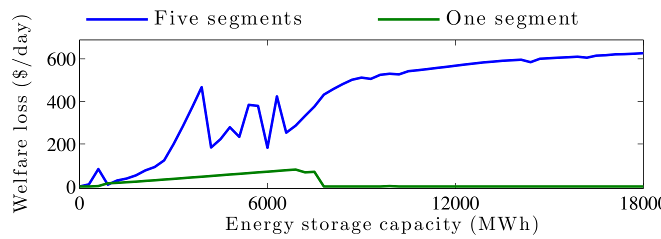

Figure 1. Social cost increase (with respect to the social optimum) due to strategic bidding of the ESS.

VI. Numerical simulations

Numerical simulations are performed using the one area IEEE RTS 24 bus system found in [17]. The system is composed of 37 generators, 38 transmission lines, and load at 17 buses. The ESS owner operates five energy storage units at buses 114, 119, 117, 120, and 123. The power and energy capacities of the ESS are varied throughout the simulations but always at a constant $\frac{\overline{SoC}_h}{\overline{q}^c_h} = \frac{200}{3}$. The system is modeled using GAMS and solved using CPLEX.

A. Effects of strategic bidding on the social welfare

By definition, strategic bidding decreases the social welfare with respect to the social optimum. The magnitude of such decrease depends on a number of factors including: load shape and magnitude, the location and size of the storage units, topology of the transmission system, market set-up, among others. In this work we use the simulations to draw *qualitative* insights and conclusions.

For instance, as shown in Fig. 1, the number of piece-wise linear segments used to model the generator's cost curve has a significant impact on the estimation of welfare loss. The loss of welfare with respect to the social optimum is largest when modeling the generator cost curves using 5 segments. Event though the magnitude of the loss of welfare is modest (it tops at roughly \$600 per day, which amounts to roughly 0.75% of the system cost) it is not possible to conclude that the welfare loss will be as small for a generic power system. In the rest of this section, we model the generator costs using 5 piece-wise segments.

It is important to note that even though strategic bidding has an adverse effect on social welfare, results suggest that it is better to have an ESS bidding strategically than no energy storage at all. As shown in Table I, the social cost with no storage is $\$90.3 \times 10^3$ while the cost under strategic bidding is $\$86.8 \times 10^3$.

B. Social welfare distribution

As shown in Fig. 1, there is always a non-negative welfare loss due to the strategic bid by the ESS. In other words, the system as a whole is never better-off compared to the social

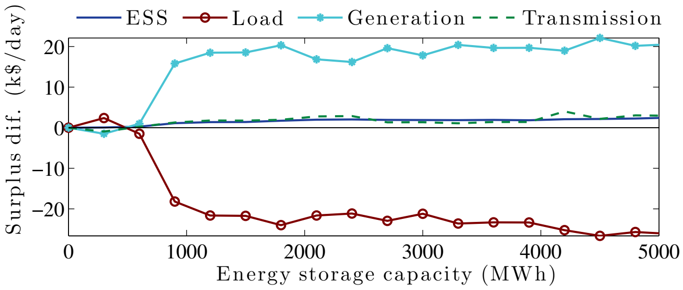

Figure 2. Surplus difference (with respect to the social optimum) due to the ESS's strategic bid for each power system actors. Positive differences denote gains while negative differences denote losses with respect to the social optimum.

Table I

	Surplus (k$)				
Model	ESS	Gen.	Trans.	Load	Social cost (k$)
No ES	0	193	10.7	807	90.3
Social optimum	1.82	178	7.06	829	86.3
Strategic bid	3.63	197	8.46	805	86.8
τ pricing	reg.	181	14.34	820	86.3

For the last 3 cases, the energy storage penetration is 3,900 MWh.

optimum. However, some players do benefit from the bidding behavior of the ESS. Naturally, the ESS benefits from its own profit maximizing behavior but as shown in Fig. 2 the other players benefit at some energy storage penetration levels and suffer at other levels.

Interestingly, the only other participant who provides arbitrage besides the ESS, the transmission system (who arbitrages energy in space), experiences profit gains that are remarkably similar to those of the ESS (see Fig. 1). The load and generation, on the other hand, experience losses and gains, respectively, that mirror each other.

C. Profit regulation and side payments

In this section we study the welfare/profit allocation among the participants. The question of whether a welfare/profit allocation is good or evil is outside the scope of this work.

Suppose that the system has an energy storage penetration of 3,900 MWh and that the SO deems the welfare distribution given by the social optimum as a desirable distribution of the social welfare. Then the SO could set the c^{reg} constant such that the ESS has a profit of $\$1.82 \times 10^3$ per day and transfer $\$17 \times 10^3$ per day to the load. These funds would have to come from the generation and transmission who, compared to the social optimum, are better off with the τ pricing scheme (see Table I for details).

If the SO deems that the a fair distribution of the welfare is such that everyone is at least as well-off as in the strategic bidding case. In that case, the SO could set up a side-payment scheme that redistributes the welfare such that everyone is better-off compared to the strategic bidding case. Note that since the social welfare is $500 per day higher using the τ pricing scheme, it is possible to make every player strictly better-off compared to the strategic bidding case.

VII. Conclusion

This paper assesses the impacts of strategic bidding by an energy storage system (ESS) on the welfare of the rest of the power system. It is shown that, as expected, strategic bidding improves the ESS's profit and reduces the social welfare with respect to the socially optimal case. Regarding less obvious results, it is also shown that while the net impacts on the system are negative, the impact on the individual players is mixed and varies with the size of the ESS. In order to mitigate the negative effects that strategic bidding has on the system, we propose a non-uniform pricing scheme, which the SO could adopt for the ESS in lieu of marginal pricing. The proposed pricing scheme *i)* incentivizes the ESS to operate in a socially optimal fashion, *ii)* is compatible with individual rationality, and *iii)* allows for the regulation of the ESS profit. The claims are validated via numeral simulations using the IEEE RTS 24 bus system.

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