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Bidding Strategy for an Energy Storage Facility

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Abstract—This paper studies operation decisions of energy storage facilities in perfectly and imperfectly competitive markets. In a perfectly competitive market, the storage facility is operated to maximize the social welfare. However, in a imperfectly competitive market, the storage facility operates to maximize its profit, while the market operator aims at maximizing the social welfare. In this case, the storage facility adapts its strategic behavior to take advantage of market conditions. To model the imperfectly competitive market, a bi-level optimization model is implemented to present the interactions between the storage facility and the market operator. In an illustrative test system, operation of the storage facility in these two market structures is compared and discussed.

Index Terms—Bidding strategy, Energy storage, Market operator, Mathematical Program with Equilibrium Constraints (MPEC)

A. Indices and Sets

t	Index of time periods running from 1 to N_t.
g	Index of generation units running from 1 to N_g.
s	Index of energy storage systems running from 1 to N_s.
d	Index of load demands running from 1 to N_d.

B. Parameters

MC_s^{dis}	Marginal cost of energy storage system s in the discharging mode, (\$/MWh).
MC_s^{ch}	Marginal cost of energy storage system s in the charging mode, (\$/MWh).
MC_g	Marginal cost of generation unit g, (\$/MWh).
$P_s^{dis,max}$	Maximum limit on generated power of energy storage system s in the discharging mode, (MW).
$P_s^{ch,max}$	Maximum limit on stored power of energy storage system s in the charging mode, (MW).
E_s^{max}	Maximum limit on stored energy of energy storage system s, (MWh).
E_s^{ini}	Initial value of stored energy of energy storage system s, (MWh).
α_s	A non-negative factor to control stored energy of energy storage system s for the the next time horizon.
η_s	Efficiency of energy storage system s.
P_g^{max}	Capacity of generation unit g, (MW).
P_g^{ini}	Initial value of generated power of generation unit g, (MW).
$P_{d,t}^{max}$	Maximum load demand of consumer d at time t, (MW).

$U_{d,t}$	Bid price of load demand d at time t, (\$/MWh).

C. Variables

$u_{s,t}^{dis}$	Binary decision variable to indicate if energy storage system s is in the discharging mode at time t.
$u_{s,t}^{ch}$	Binary decision variable to indicate if energy storage system s is in the charging mode at time t.
$u_{s,t}^{idl}$	Binary decision variable to indicate if energy storage system s is in the idle mode at time t.
$\overline{P}_{s,t}^{dis}$	Quantity offer by energy storage system s in the discharging mode at time t, (MW).
$\overline{P}_{s,t}^{ch}$	Quantity bid by energy storage system s in the charging mode at time t, (MW).
$p_{g,t}$	Power generated by generation unit g at time t, (MW).
$p_{s,t}^{dis}$	Power generated by energy storage system s in the discharging mode at time t, (MW).
$p_{s,t}^{ch}$	Power stored by energy storage system s in the charging mode at time t, (MW).
$o_{s,t}^{dis}$	Price offer by energy storage system s in the discharging mode at time t, (\$/MWh).
$o_{s,t}^{ch}$	Price bid by energy storage system s in the charging mode at time t, (\$/MWh).
$e_{s,t}$	Energy stored in energy storage system s at time t, (MWh).
$p_{d,t}$	Power consumed by load demand d at time t, (MW).
μ, λ	Dual variables corresponding to the lower level constraints.

I. INTRODUCTION

Large-scale electric energy storage is being considered as one of the potential enablers for a more flexible grid, and thus is expected to grow significantly over the coming years [1]. As an example, California has set a goal of feeding 33% of its energy through renewable resources [2], 80% of which to be coming from wind and solar generation [3]. To accommodate this much intermittent energy, the California Public Utilities Commission has mandated the three big utilities to have 1325 MW of energy storage in operation by 2024 [4]. Besides, the Federal Energy Regulatory Commission (FERC) allows energy storage, as one of so-called "non-generation" resources, to participate in electricity markets [5]. Therefore, exploring

optimal operational strategies for large-scale energy storage resources is of particular interest.

Over the past few years, a number of works have been reported which are focused on operation of energy storage. In particular, the existing literature on the optimal operation of energy storage systems can be divided into two broad categories depending on who operates the facility. In the first category, energy storage facilities are operated in a centrally controlled market. In such context, energy storage may serve a number of purposes, such as, improving system reliability or facilitating high renewable energy penetration. In [6] and [7], a compressed air energy storage and a pumped-storage hydro, as the two largest worldwide installed storage facility technologies, are employed to reduce the total generation cost for a system with high wind penetration. In [8], impacts of energy storage in terms of power system reliability on a system with integrated renewable energy resources are discussed. In [9], plug-in vehicles as mobile storage devices are used to maximize the utilization of renewable energy resources in terms of cost and emission. In [10], the optimal capacity and operation for a storage facility is optimized to minimize the total system operation cost and also its impact on price is explored. In this category of studies, energy storage is not considered as an independent for-profit entity, and thus, its profitability is not addressed.

In the second category, energy storage is operated as a merchant and for-profit entity. These studies can further be divided into two groups depending on how the storage facility would impact market prices. In the first group, the storage facilities are treated as price-takers, i.e., they are assumed to be small enough such that their actions do not affect market prices. In such context, operation of the storage facilities is optimized under the assumption that the future market prices are known in advance. Hence, the storage operator would use historical price data, and optimizes its operation decisions accordingly. In [11], an energy storage facility is owned by a wind farm and its operation decisions are made according to the wind farm's power production estimates in order to maximize the owner's profit. In [12], a few distributed storage systems are operated by an aggregator to meet the local load demand at the minimum cost. In [13], a storage facility is operated by an independent utility to maximize its profit in both energy and reserve markets. In the second group, the energy storage facilities are considered as price-makers [14], i.e., they are large and their actions actually impact market prices. In this group of studies, the facilities, which have the price-maker capability and their objective is to maximize their profit, can bid not necessary at their marginal cost. This may lead to an imperfectly competitive market environment.

To investigate the optimal bidding strategies of market players in an imperfect competitive market environment, several studies have reported the application of Mathematical Program with Equilibrium Constraints (MPEC) models [14], [15], [16], [17], [18], [19]. The MPEC approach for electricity market modeling was initially used in the pioneering work [15]. Other studies followed by using the MPEC approach in other electricity market studies, such as, on strategic behavior of a producer in [16], the optimal investment of a strategic producer in [17], the strategic offering of a wind power producer in [18], the strategic bidding of a large consumer in [19], and the strategic bidding of a storage facility [14].

In addition, several relevant papers exist in the technical literature addressing the perfect and imperfect competitions in power systems, e.g., [20] referring to the offering strategy of producers, and [21] referring to the transmission expansion planning. In these two papers, a Cournot model is used to model the imperfect competition. Their findings show that each market player with market power capability can potentially adapt its strategy considering the market conditions to alter the market-clearing outcomes to its own benefit. In this paper, we compare the storage facility's operation in perfectly and imperfectly competitive markets. The operation of storage facility for each hour in both cases is discussed with details.

The main contribution of this paper is to compare the storage facility's operation in two market circumstances. This study provides a good understanding of market structures' impacts on storage facilities' operation decisions.

The rest of the paper is organized as follows. The methodology and formulation are provided in Section II. The results are presented and discussed in Section III. The paper is concluded in Section IV.

II. METHODOLOGY AND FORMULATION

In this section, the proposed method for determining the optimal bidding strategy of a storage facility in perfectly and imperfectly competitive market structures are presented.

A. Storage Facilities' Operation in a Perfectly Competitive Market

In a perfectly competitive market, all market players offer at their marginal costs. The market operator accepts the bids and offers to maximize the social welfare and satisfy the physical market constraints. This problem is formulated in (a.1)-(a.6) as given below:

Min. $\sum_{t=1}^{N_t} \Big[\sum_{g=1}^{N_g} MC_g.p_{g,t} + \sum_{s=1}^{N_s} MC_{s,t}^{dis}.p_{s,t}^{dis}$

$$- \sum_{s=1}^{N_s} MC_{s,t}^{ch}.p_{s,t}^{ch} - \sum_{d=1}^{N_d} U_{d,t}.p_{d,t} \Big] \qquad (a.1)$$

S.t.

$$\sum_{d=1}^{N_d} p_{d,t} - \sum_{s=1}^{N_s} [p_{s,t}^{dis} - p_{s,t}^{ch}] - \sum_{g=1}^{N_g} p_{g,t} = 0 \quad : \lambda_t; \quad \forall t \quad (a.2)$$

$$0 \leq p_{g,t} \leq P_g^{max} \quad \forall g, \forall t \qquad (a.3)$$

$$0 \leq p_{d,t} \leq P_{d,t}^{max} \quad \forall d, \forall t \qquad (a.4)$$

$$0 \leq p_{s,t}^{dis} \leq P_s^{dis,max} \quad \forall s, \forall t \qquad (a.5)$$

$$0 \leq p_{s,t}^{ch} \leq P_s^{ch,max} \quad \forall s, \forall t \qquad (a.6)$$

The objective function of this problem seeks to minimize the negative of social welfare, which is the difference between generation cost and demand utility, as presented in (a.1). (a.2) enforces the energy balance, whose dual variable provides the system marginal cost (SMC). (a.3) binds generators' production levels. (a.4) binds the consumption level of load demands. (a.5) and (a.6) enforce the energy storage facilities to discharge/charge between zero and their maximum capacities, respectively.

B. Storage Facilities' Operation in an Imperfectly Competitive Market Environment

In this section, the storage facility's operation in an imperfectly competitive market environment is formulated using a bi-level model. This model has two components, i.e., an upper level problem modeling the operation of the storage facility and the lower problem, i.e., modeling the market-clearing process. The upper and lower level problems are first discussed, and then, the bi-level model is transformed into a single-level MPEC and solved accordingly.

The upper level problem seeks to maximize the storage facility's profit, as formulated in (b.1)-(b.10):

Min.
$$\sum_{t=1}^{N_t} \sum_{s=1}^{N_s} \Big[(\lambda_t + MC_s^{ch}).p_{s,t}^{ch}$$
$$- (\lambda_t - MC_s^{dis}).p_{s,t}^{dis} \Big] \tag{b.1}$$

S.t.
$$u_{s,t}^{dis} + u_{s,t}^{ch} + u_{s,t}^{idl} = 1 \quad \forall s, \forall t \tag{b.2}$$
$$0 \le \overline{p}_{s,t}^{dis} \le u_{s,t}^{dis}.P_s^{dis,max} \quad \forall s, \forall t \tag{b.3}$$
$$0 \le \overline{p}_{s,t}^{ch} \le u_{s,t}^{ch}.P_s^{ch,max} \quad \forall s, \forall t \tag{b.4}$$
$$o_{s,t}^{dis} \ge 0 \quad \forall s, \forall t \tag{b.5}$$
$$o_{s,t}^{ch} \ge 0 \quad \forall s, \forall t \tag{b.6}$$
$$0 \le e_{s,t} \le E_s^{max} \quad \forall s, \forall t \tag{b.7}$$
$$e_{s,t} = E_s^{ini} - p_{s,t}^{dis} + \eta_s.p_{s,t}^{ch} \quad \forall s, t = 1 \tag{b.8}$$
$$e_{s,t} = e_{s,(t-1)} - p_{s,t}^{dis} + \eta_s.p_{s,t}^{ch} \quad \forall s, \forall t > 1 \tag{b.9}$$
$$e_{s,t} = \alpha_s.E_s^{ini} \quad \forall s, t = N_t \tag{b.10}$$

The objective function (b.1) is composed of two terms. The first term is associated with the cost incurred for purchasing and storing energy in the charging mode. It is composed of the cost of buying energy from market and the costs of that might be associated to storing this energy by the energy storage charging device (e.g., the costs of compression in the case of compressed air energy storage). The second term is associated with the energy storage profit in discharging mode, which is calculated through the revenue achieved by selling energy to the market minus the costs that might be associated with releasing the stored energy (e.g., the expanding costs in the case of compressed air energy storage). Note that SMC (λ_i) is endogenously obtained from the lower level problem.

Three operation modes for the energy storage facility are considered in (b.2), which are discharging, charging, and idling, i.e., when the facility is operating in neither discharging nor charging modes. (b.3) and (b.4) bind the energy storage quantity offers and bids, respectively. (b.5) and (b.6) enforce the non-negativity of the energy storage offer and bid prices, respectively. (b.7) refers to upper and lower bounds for the storage facility energy reservoir. (b.8) and (b.9) represent the energy storage state of charge for the first and rest of hours, respectively. (b.10) is designed to specify the state of charge at the end of planning horizon. For sake of simplicity, transmission system constraints are not modeled.

In the lower level problem, the market operator clears the market based on submitted bids and offers. The storage facility strategically offers/bids in both quantity and price. We assume that other market participants submit their offer and bid prices based on their marginal cost/utility. This assumption enables us to model the problem of this paper as an MPEC problem, in line with [15]. The lower level problem is formulated in by (c.1)-(c.6), which are similar to (a.1)-(a.6). However, (a.5) and (a.6) are substituted by (c.5) and (c.6) which restrict the discharging and charging power of energy storage facilities by their submitted quantity offers and bids.

Min.
$$\sum_{t=1}^{N_t} \Big[\sum_{g=1}^{N_g} MC_g.p_{g,t} + \sum_{s=1}^{N_s} o_{s,t}^{dis}.p_{s,t}^{dis}$$
$$- \sum_{s=1}^{N_s} o_{s,t}^{ch}.p_{s,t}^{ch} - \sum_{d=1}^{N_d} U_{d,t}.p_{d,t} \Big] \tag{c.1}$$

S.t.
$$\sum_{d=1}^{N_d} p_{d,t} - \sum_{s=1}^{N_s} [p_{s,t}^{dis} - p_{s,t}^{ch}] - \sum_{g=1}^{N_g} p_{g,t} = 0 \quad : \lambda_t; \quad \forall t \tag{c.2}$$
$$0 \le p_{g,t} \le P_g^{max} : \mu_{g,t}^{min}, \mu_{g,t}^{max}; \quad \forall g, \forall t \tag{c.3}$$
$$0 \le p_{d,t} \le P_{d,t}^{max} : \mu_{d,t}^{min}, \mu_{d,t}^{max}; \quad \forall d, \forall t \tag{c.4}$$
$$0 \le p_{s,t}^{dis} \le \overline{p}_{s,t}^{dis} : \mu_{s,t}^{dis,min}, \mu_{s,t}^{dis,max}; \quad \forall s, \forall t \tag{c.5}$$
$$0 \le p_{s,t}^{ch} \le \overline{p}_{s,t}^{ch} : \mu_{s,t}^{ch,min}, \mu_{s,t}^{ch,max}; \quad \forall s, \forall t \tag{c.6}$$

The dual variables pertaining to constraints above are specified at each equation. Note that the binary decisions, as well as the offering and bidding decisions of the energy storage (price and quantity) are upper level variables. However, they are fixed values within the lower level problem. Therefore, the lower level problem is continuous, linear, and thus convex [19].

In order to transfer the bi-level model into a single-level MPEC, the primal-dual transformation is applied [22]. (d.1)-(d.7) provided in the Appendix give the dual constraints of the lower level problem. Equation (d.8) refers to the strong duality condition corresponding to the lower level problem, which enforces the equality of its primal and dual objective function values at the optimal solution.

TABLE I
GENERATION UNITS CHARACTERISTICS

Unit No.	Bus No.	P_g^{max} (MW)	MC_g ($/MWh)	RU_g^{max} (MW/h)	RD_g^{max} (MW/h)	P_g^{ini} (MW)
G1	1	100	12	20	20	100
G2	2	75	20	12	12	75
G3	6	50	50	10	10	0
G4	6	50	300	10	10	0

TABLE II
STORAGE FACILITY CHARACTERISTICS

Storage facility	Bus No.	$P_s^{dis,max}$ (MW)	$P_s^{ch,max}$ (MW)	MC_s^{dis} ($/MWh)	MC_s^{ch} ($/MWh)
1	5	20	15	18	1

Figure 1. Demand over 24 hours, $(\sum_d P_{d,t}^{max}, \forall t)$

The single-level MPEC problem includes upper level problem (b.1)-(b.10), primal constraints (c.2)-(c.6), dual constraints (d.1)-(d.7) and strong duality condition (d.8). There are some non-linear terms in the MPEC formulation due to the product of prices and quantities in (d.8) and (b.1). Note that since there are also binary variables within MPEC, it is in fact a mixed-integer non-linear programming problem, while there is no off-the-shelf solver available to solve this kind of problems. Thus, pursuing linearity, the strong duality condition as well as the primal inequality constraints and the non-negativity conditions can be replaced by the set of complementary conditions obtained by Karush-Kuhn-Tucker (KKT) conditions of the lower level problem (e.1)-(e.8) [22], [23].

Each of complementarity conditions can be linearized by its mixed-integer linear equivalent as explained in [24]. Also, the linear equivalent of objective function (b.1) can be driven from dual conditions, the strong duality condition, and the complementarity conditions [16]. The linear objective function is stated in Appendix as (f.1).

III. NUMERICAL RESULTS

In this section, a six-bus system [25] is studied to demonstrate the storage operation in two market structures.

Technical characteristics of the generation units are given in Tables I. The storage facility technical characteristics are provided in Table II. The energy storage's charging and discharging components are modeled separately. This is mainly inspired by the operation of a compressed air energy storage facility [26]. This separation provides further flexibility in modeling and analysis of different storage technologies. The capacity of storage facility's energy reservoir is assumed to be 100 MWh. In this test system, a period of 24 hours is considered as the planning horizon. The planning horizon for the bidding strategy of energy storage is selected to reasonably match the storage reservoir size [27], larger reservoirs may require a longer planning period. It is assumed that the facility starts empty and comes back to the same state at the end of the planning horizon. Also, without losing generality, the efficiency of both charge and discharge devices are supposed to be 100%. The hourly load distribution over the 24 hours horizon is shown in Fig. 1. The load is distributed equally among buses 3 and 4. All loads bid at $450/MWh for all hours.
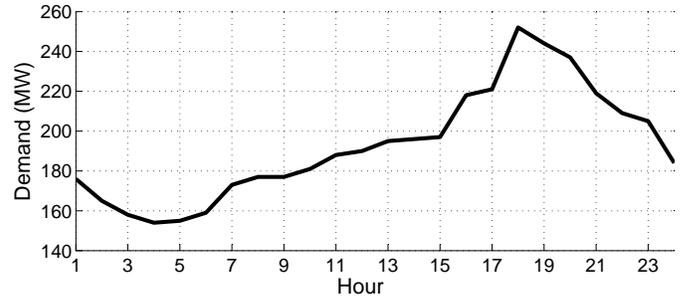
The following test cases are studied:
- Case 1: The energy storage, which is operated by the market operator, participates in the perfectly competitive market.
- Case 2: The energy storage, which is controlled by an independent operator, bids and offers strategically to maximize its profit in the imperfectly competitive market.

Case 1: In this case, we assume the storage facility participates in the market as a non-strategic player, and thus, the market is perfectly competitive. The detailed numerical results for this case are presented in Table III. We have also presented the consumption values at each hour in this table. The purpose of this case is to demonstrate a simple case where the numerical results could be tracked. Also, we will compare the results of other cases to this base case.

In the first hour, the load is 176 MW and is supplied by generation units G1, G2, and G3. Since generation units G1 and G2 are dispatched at their full capacity in this hour, the marginal cost of generation unit G3 sets the SMC, which is $50/MWh. In the second hour, the load is 165 MW and the storage facility is charged at a 10 MW rate. The SMC is cleared at $31/MWh, which is less than the marginal cost of the generation unit who can supply the next MW demand, i.e., unit G3. To justify this value, observe that in this hour, the next MW could be supplied by unit G2 if the storage facility was being charged one less MW. The value of this MW is equal to the would be selling price when discharging, i.e., $50/MWh at either of hours except for hours that the storage is fully dispatched (e.g., hour 18), minus the storage facility's operation costs in charging and discharging modes, i.e., 18+1=19 $/MWh. Thus, the SMC of the second hour is calculated 50-19=31 $/MWh. Hours 3-6 are considered as low demand periods and thus, the storage facility is charged at the maximum rate, i.e., 15 MW. In these hours, the SMC is determined by the marginal cost of generation unit G2, i.e., $20/MWh. Similar to hour 2, the SMC at hour 7 is $31/MWh. For hours 8-17, the SMC is $50/MWh, which is equal to the marginal cost of generation unit G3. At hour 18, the load demand is 246 MW and the SMC is determined by the marginal cost of the most expensive unit, i.e., G4. Note

Hour	$p_{d,t}$ (MW)	$p_{s,t}^{dis}/p_{s,t}^{ch}$ (MW)*	$p_{g,t}$ G_1	G_2	G_3 (MW)	G_4	$\lambda_{i,t}$ ($/MWh)
1	176		100	75	1	0	50
2	165	-10	100	75	0	0	31
3	158	-15	100	73	0	0	20
4	154	-15	100	69	0	0	20
5	155	-15	100	70	0	0	20
6	159	-15	100	74	0	0	20
7	173	-2	100	75	0	0	31
8	177		100	75	2	0	50
9	177		100	75	2	0	50
10	181		100	75	6	0	50
11	188		100	75	13	0	50
12	190		100	75	15	0	50
13	195		100	75	20	0	50
14	196		100	75	21	0	50
15	197		100	75	22	0	50
16	218		100	75	43	0	50
17	221	12	100	75	34	0	50
18	252	20	100	75	50	7	300
19	244	20	100	75	49	0	50
20	237	20	100	75	42	0	50
21	219		100	75	44	0	50
22	209		100	75	34	0	50
23	205		100	75	30	0	50
24	184		100	75	9	0	50

* A negative/positive value corresponds to the storage facility charging/discharging mode.

Case No.	Storage	G1	G2	G3	G4	All Gen. units
Case 1	5.660	100.4	60.9	12.5	0	173.8
Case 2	13.542	148.2	96.75	37.5	0	282.45

Hour	$p_{d,t}$ (MW)	Storage facility $p_{s,t}^{dis}/p_{s,t}^{ch}$ (MW)	$o_{s,t}^{dis}/o_{s,t}^{ch}$ ($/MWh)	$p_{g,t}$ G_1	G_2	G_3 (MW)	G_4	$\lambda_{i,t}$ ($/MWh)
1	176			100	75	1	0	50
2	165	-10	20	100	75	0	0	20
3	158	-15	20	100	73	0	0	20
4	154	-15	20	100	69	0	0	20
5	155	-15	20	100	70	0	0	20
6	159	-15	20	100	74	0	0	20
7	173	-2	20	100	75	0	0	20
8	177			100	75	2	0	50
9	177			100	75	2	0	50
10	181			100	75	6	0	50
11	188			100	75	13	0	50
12	190			100	75	15	0	50
13	195			100	75	20	0	50
14	196			100	75	21	0	50
15	197	20	50	100	75	2	0	50
16	218			100	75	43	0	50
17	221			100	75	46	0	50
18	252	20	300	100	75	50	7	300
19	244	19	300	100	75	50	0	300
20	237	12	300	100	75	50	0	300
21	219			100	75	44	0	50
22	209			100	75	34	0	50
23	205	1	50	100	75	29	0	50
24	184			100	75	9	0	50

that for hours 19 and 20, operation of the storage facility has led to a lower SMC of $50/MWh. This is because if the storage facility were not operating, the demand would have been met by generation unit G4, and the SMC would have been $300/MWh at these two hours. However, since the storage facility discharges energy back to the system during these hours, the SMC remains at the marginal cost of unit G3, i.e., $50/MWh. Thus, operation of the storage has reduced the market price for theses hours. For the remaining hours, i.e., 21-24, unit G3 sets the price at $50/MWh. The total profit in this case is $5660 for the storage facility, and $173800 for the rest of the fleet. The profits of the storage facility and other generation units for this case, and all other cases, are summarized in Table IV.

Case 2: The market outcomes for this case are presented in Table V. The results obtained for hour 1 are identical to those of Base Case. For hour 2, the storage facility strategically bids to buy 10 MW at $20/MWh, which is identical to the marginal cost of generation unit G2. The storage facility bids such that there is no need to dispatch generation unit G3. Thus, the demand is supplied by generation units G1 and G2. The SMC for this hour is identical to the marginal cost of the last generation unit dispatched and the bid price of the last demand supplied (i.e., storage), that is $20/MWh. For hours 3-7, the storage facility price bid is the same as hour 2. The storage

facility stays in the idle mode during hours 8-14 and 16-17, and discharges at its maximum level at hour 15. For hour 18, it strategically offers its maximum discharge level at a price identical to the marginal cost of unit G4. This way, the SMC is determined by the marginal cost of unit G4, $300/MWh. For hour 19, the storage facility offers strategically 19 MW at $300/MWh. Through this strategy, generation unit G3 is dispatched to its maximum level and the next MW should be supplied by unit G4. Therefore, the SMC stays at $300/MWh. Similarly, for hour 20, the storage facility offers 12 MW at $300/MWh. The storage facility offers its remaining one MWh during hour 23 at price of $50/MWh to meet the initial charging condition for next day.

The hourly SMCs for Cases 1 and 2 are illustrated in Fig. 2. The figure shows how the strategic behavior of the storage facility impacts the hourly SMCs, i.e., lower SMCs when it charges and higher SMCs when it discharges. Note that if the storage facility plays based on its marginal cost, the storage facility compared to a case in which there is no storage facility in the system, increases and decreases the market price in charging and discharging modes, respectively. The reason lies in supply and demand balance constraints. In an imperfect competition, as explained in Case 2, the facility through this strategic bidding avoids such impacts on market price. From this figure and also the results reflected in Table IV, the impact on prices in Case 2 benefits not only the storage facility, but also other generators. Overall, and among all the units, the peaking ones experience the highest increase in their profit as they only generate during the higher price hours.

IV. CONCLUSION

This paper compares and studies the bidding strategy of a price-maker storage facility in both perfectly and imperfectly competitive markets. The storage operation in both market
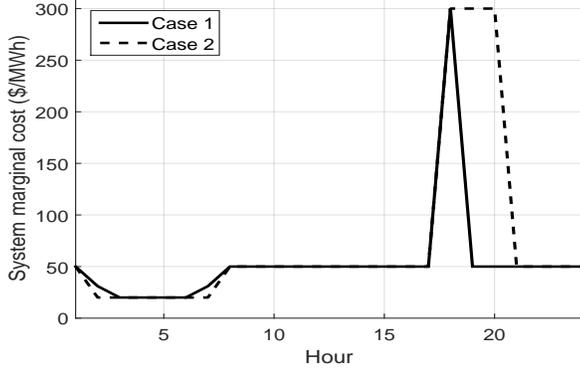
Figure 2. Comparing the hourly SMCs between Cases 1 and 2

structures is formulated. To model an imperfectly competition market, a bi-level model is implemented to present the interactions between the storage facility and the market operator. The primal-dual and KKT conditions are applied to transform the bi-level problem into an MPEC, that can be recast as a Mixed Integer Linear Programming (MILP). In both perfect and imperfect competitions, impacts of storage facility's operation decisions on hourly SMCs and generation schedule are presented and discussed. In an imperfect competition, the merchant storage facility was found to adjust its operation strategies to take advantage of existing circumstances in the market to increase its profit.

APPENDIX

The dual of the lower level problem is stated as follows:

$$o_{s,t}^{dis} - \lambda_t + \mu_{s,t}^{dis,max} - \mu_{s,t}^{dis,min} = 0 \quad \forall s, \forall t \tag{d.1}$$

$$-o_{s,t}^{ch} + \lambda_t + \mu_{s,t}^{ch,max} - \mu_{s,t}^{ch,min} = 0 \quad \forall s, \forall t \tag{d.2}$$

$$MC_g - \lambda_t + \mu_{g,t}^{max} - \mu_{g,t}^{min} = 0 \quad \forall g, \forall t \tag{d.3}$$

$$-U_{d,t} + \lambda_t + \mu_{d,t}^{max} - \mu_{d,t}^{min} = 0 \quad \forall d, \forall t \tag{d.4}$$

$$\mu_{g,t}^{max}, \mu_{g,t}^{min} \geq 0 \quad \forall g, \forall t \tag{d.5}$$

$$\mu_{d,t}^{max}, \mu_{d,t}^{min} \geq 0 \quad \forall d, \forall t \tag{d.6}$$

$$\mu_{s,t}^{dis,max}, \mu_{s,t}^{dis,min}, \mu_{s,t}^{ch,max}, \mu_{s,t}^{ch,min} \geq 0 \quad \forall s, \forall t \tag{d.7}$$

$$\sum_{t=1}^{N_t} \Big[\sum_{g=1}^{N_g} MC_g.p_{g,t} + \sum_{s=1}^{N_s} o_{s,t}^{dis}.p_{s,t}^{dis}$$
$$- \sum_{s=1}^{N_s} o_{s,t}^{ch}.p_{s,t}^{ch} - \sum_{d=1}^{N_d} U_{d,t}.p_{d,t} \Big] =$$
$$- \sum_{t=1}^{N_t} \sum_{s=1}^{N_s} \big[\mu_{s,t}^{dis,max}.\overline{p}_{s,t}^{dis} + \mu_{s,t}^{ch,max}.\overline{p}_{s,t}^{ch} \big]$$
$$- \sum_{t=1}^{N_t} \sum_{g=1}^{N_g} \mu_{g,t}^{max}.P_g^{max} - \sum_{t=1}^{N_t} \sum_{d=1}^{N_d} \big[\mu_{d,t}^{max}.P_{d,t}^{max} \big] \tag{d.8}$$

The KKT conditions of the lower level are stated as follows:

$$0 \leq p_{g,t} \perp \mu_{g,t}^{min} \geq 0 \quad \forall g, \forall t \tag{e.1}$$

$$0 \leq (P_g^{max} - p_{g,t}) \perp \mu_{g,t}^{max} \geq 0 \quad \forall g, \forall t \tag{e.2}$$

$$0 \leq p_{d,t} \perp \mu_{d,t}^{min} \geq 0 \quad \forall d, \forall t \tag{e.3}$$

$$0 \leq (P_{d,t}^{max} - p_{d,t}) \perp \mu_{d,t}^{max} \geq 0 \quad \forall d, \forall t \tag{e.4}$$

$$0 \leq p_{s,t}^{dis} \perp \mu_{s,t}^{dis,min} \geq 0 \quad \forall s, \forall t \tag{e.5}$$

$$0 \leq (\overline{p}_{s,t}^{dis} - p_{s,t}^{dis}) \perp \mu_{s,t}^{dis,max} \geq 0 \quad \forall s, \forall t \tag{e.6}$$

$$0 \leq p_{s,t}^{ch} \perp \mu_{s,t}^{ch,min} \geq 0 \quad \forall s, \forall t \tag{e.7}$$

$$0 \leq (\overline{p}_{s,t}^{ch} - p_{s,t}^{ch}) \perp \mu_{s,t}^{ch,max} \geq 0 \quad \forall s, \forall t \tag{e.8}$$

The linearized objective function is stated as follows:

$$\textbf{Min.} \quad \sum_{t=1}^{N_t} \sum_{s=1}^{N_s} \big[MC_s^{dis}.p_{s,t}^{dis} + MC_s^{ch}.p_{s,t}^{ch} \big]$$
$$+ \sum_{t=1}^{N_t} \sum_{g=1}^{N_g} MC_g.p_{g,t} - \sum_{t=1}^{N_t} \sum_{d=1}^{N_d} U_{d,t}.p_{d,t}$$
$$+ \sum_{t=1}^{N_t} \sum_{g=1}^{N_g} \big[\mu_{g,t}^{max}.P_g^{max} \big] + \sum_{t=1}^{N_t} \sum_{d=1}^{N_d} \big[\mu_{d,t}^{max}.P_{d,t}^{max} \big] \tag{f.1}$$

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