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Bidding Strategy in Energy and Spinning Reserve Markets for Aluminum Smelters' Demand Response

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***Abstract*—Aluminum smelting is an energy-intensive electrolytic process that is widely used to produce aluminum. The electricity cost thereby constitutes a significant portion of the total operation cost. At the same time, the smelting process is able to change its power consumption both accurately and quickly by controlling the pots' DC voltage, without affecting the production quality. Hence, an aluminum smelter has both the motivation and the ability to participate in demand-side management. By bidding into the electricity market, the smelter provides flexibility to the power system operator and gets compensation which reduces the overall electricity cost. In this paper, we focus on determining the optimal bidding strategy in the day-ahead energy and spinning reserve markets for an aluminum smelter. The approach is based on stochastic programming in which the market prices are the stochastic variables. Case studies demonstrate the effectiveness of the approach and provide insights into the demand-side management for industrial plants.**

***Index Terms*—Demand response, stochastic programming, industrial load, bidding strategy, electricity market.**

I. Introduction

Demand response is widely recognized as an opportunity to reduce the carbon footprint of electric power systems because the flexibility provided by loads can be utilized to balance the variability of renewable resources such as wind and solar energy thereby supporting their growing penetration [1]. Given that loads are often able to respond faster to operator requests than generators, as the generators need longer time to change their output and ensure operation safety according to the generators' dynamics [2] [3], demand response resources may be highly useful for fast short-term balancing services.

Energy intensive processes are particularly suitable for demand side management (DSM) if they are reasonably flexible in terms of their power consumption. A growing literature investigates how to optimally adjust the schedule of industrial processes to provide demand response. In [4], the potential utilization of industrial processes for DSM in German electricity markets is investigated. Aluminum smelters along with several other industrial loads such as electric arc furnace steel plants are identified as energy intensive processes that can provide demand response services. The applications of DSM in several industrial sectors including aluminum smelting, food processing, greenhouse, and ice storage are summarized in [5] and [6]. DSM provided by the cement industry are discussed in [7] and [8], in which the spinning reserve provision and the energy cost minimization under time-based electricity prices are investigated, respectively. The steel industry also draws attention from the research community: the peak load management for a steel plant is studied in [9]; how to track a pre-specified energy curve is investigated in [10] and [11]; the optimal scheduling of production activities are studied by resource-task network models in [12]. In terms of the aluminum smelting industry, [3] introduces the pilot experiences of demand response at Alcoa Warrick Operation, and [13] studies the optimal regulation provision by aluminum smelting plants using stochastic optimization with linearized AGC trajectories as scenarios. All of the work mentioned above focuses on how to optimally operate the industrial plants assuming given prices and/or requested demand reduction/increase without consideration of how the industrial plants should bid into the electricity markets.

Since the 1980s the electricity markets worldwide have been gradually evolving from monopoly markets into liberalized markets which encourage competition and improve efficiency. Along with the electricity market revolution, the research community has contributed on developing optimal participation strategy for market participants. As reviewed in [14], various methods and tools to develop an optimal bidding strategy for a conventional power producer in an electricity market have been proposed. In [15], a particular focus is put on bidding strategies for hydro-electric producers. Thereby, stochastic programming is a common mathematical approach to deal with the uncertainties of market prices [16], wind power [17], and hydro inflows [18]. In such a formulation, scenarios represent the set of possible future outcomes of the stochastic variables. Most of the approaches focus on the bidding into the energy market but stochastic programming may also be used to determine optimal bidding into the ancillary service markets [19] [20].

In this paper, we develop the optimal bidding strategy for an aluminum smelter in the day-ahead markets for both energy and spinning reserve. Our approach is based on stochastic optimization in which the markets prices are treated as stochastic variables. The remaining of the paper is organized as follows: Section II describes the aluminum smelter and its ability to provide demand response by participating in the electricity market. Section III describes the mathematical formulation for the determination of the optimal bidding strategy. Section IV demonstrates the effectiveness of the proposed model through case studies. Section V draws the conclusion of this study and describes future research directions.

II. Problem Statement

Aluminum smelting is the electrolytic process that transforms alumina to aluminum - the most widely used nonferrous metal that is used anywhere from making cars to packaging cans. In the smelting plant, the electrolytic process takes place in the so-called cell and is enabled by a DC electric current that passes through the cell. In addition to the main material alumina, several other elements are added to facilitate the chemical reaction. The cells, or pots, are connected in series to form a potline of hundreds of pots. The total power consumption of a potline can be hundreds of MWs. Typically, there are several potlines in an aluminum smelter.

The power consumption of a potline can be manipulated by adjusting the voltage at the output of the rectifier that supports the required DC current to the potline. By doing so, the power consumption rate can be adjusted very quickly and accurately, e.g. a potline can change its power consumption by about 1 MW within seconds. Another way to achieve power consumption flexibility is to shut down an entire potline totally by switching the breaker, which is able to generate a larger amount of power change within a short amount of time. However, when providing flexibilities by either controlling the rectifier or switching the breaker, the thermal balance of the pots must be maintained to ensure safe operation, i.e. the temperature of the pots must be maintained within given bounds, to ensure production efficiency and equipment safety. The smelter's flexibility enabled in this way makes aluminum smelting an ideal demand response resource (DRR). In fact, Alcoa Warrick Operation is actively participating in the MISO electricity market [3], providing both energy and ancillary services to MISO as a *DRR-Type-2* resource [21].

In this paper, we design the optimal bidding strategy for energy and spinning reserve for an aluminum smelter in the day-ahead electricity market. We assume that the smelter's flexibility is realized by controlling the rectifiers, and the smelter's power consumption is adjustable within a given range. We only consider controlling rectifiers to achieve flexibility because turning off an entire potline causes significantly more interruption to the plant operation. It is assumed that the smelter has a long-term energy contract with the electricity utility, and the smelter can sell energy back to the market if the actual amount of energy usage is less than the contracted amount. In addition, the smelter can provide spinning reserve to the power system when its power consumption is higher than its lower bound. In that case, the difference between the current loading level and the minimum loading level is the maximum available spinning reserve.

If the future market prices can be predicted accurately, the derivation of the optimal bidding strategy is fairly straightforward. Even though there is a vast amount of literature on electricity price prediction, it is still a difficult task and the existing methods are not accurate enough to provide a reliable point-price prediction. However, by employing the prediction techniques proposed in the literature, we can obtain a distribution of future prices that we can incorporate into a stochastic optimization formulation using a set of possible price scenarios. The objective of such stochastic optimization is to optimize the smelter's decisions to maximize the average profit (or expected profit) over all scenarios. The stochastic programming approach is able to hedge the risk from prediction uncertainty. We do not cover specific prediction techniques in this paper as prediction is not our focus. We assume the set of possible price scenarios are already available for our model. In addition, we assume that the smelter's bidding/offering into the electricity markets generally will not impact the final market clearing prices. This is reasonable as the smelting plant's total power capacity is small compared to the power system's total generation capacity.

In terms of bidding rules in the day-ahead markets, the DRR must submit its offers of energy and spinning reserve in the day-ahead market before both prices are known. Energy offers should take the form of a price curve (either a block offer or a slope offer), and up to ten Price/MW pairs can be submitted for each hour of the next operating day. While for spinning reserve, only one Price/MW pair can be offered for each hour of the next operating day. In terms of offering strategy for spinning reserve, it is advantageous if as much as possible of the available spinning reserve from the smelter is cleared. This is because the power system control center seldom dispatches spinning reserve and the smelter can make impressive profits simply by standing by. For example, the spinning reserve deployment rate at Alcoa Warrick Operation is less than 0.5% according to [3]. Thus, it is wise for the smelter to ask for a relatively low price to sell its maximum spinning reserve amount. After all, the spinning reserve is sold at the market clearing price which will not be affected by the smelter's offer, as the smelter's capacity is too small compared to the system capacity.

III. Mathematical Formulation

The market prices are treated as stochastic variables where $\lambda_{s,h}$ represents the energy price and $\rho_{s,h}$ stands for the spinning reserve price. The subscript h denotes the hour of the day and s denotes the scenario index. As previously mentioned, the values for these stochastic variables can be obtained by price prediction techniques. The potline's power consumption level is $P_{l,s,h}$, where l stands for the potline index. The decision variables are the smelter's offers for the day-ahead market, i.e. the energy offer Price/MW pairs and the spinning reserve offer MW/Price pair. For energy offers, we use $E_{s,h}$ to represent the energy to sell in scenario s at hour h. After the optimal values for $E_{s,h}, s = \{1, ..., S\}$ is obtained from the proposed model, the hourly energy offering curve is constructed by connecting the MW/Price pairs ($E_{s,h}$, $\lambda_{s,h}$) from different scenarios in the same hour. For spinning reserve offering, since only one Price/MW pair can be submitted for each hour, we denote this offered capacity as V_h. Note that there is no subscript s for the spinning reserve offer. Once cleared, the smelter needs to make sure that the committed amount of spinning reserve is available for any possible scenario.

The potline's power consumption is bounded by parameters P_l^{min} and P_l^{max}, which are given by the maximum achievable flexibility of the plant and the limitations to ensure a safe operation of the plant. The power consumption of $P_{l,s,h}$ is modeled by piece-wise linear segments. This is because we model the aluminum production efficiency by a piece-wise linear approximation. The number of segments is n_l and the ascending parameters $\{a_{l,1}, ..., a_{l,n_l+1}\}$ represent the segments. Note that $a_{l,1}, a_{l,n_l+1}$ equal P_l^{min}, P_l^{max}, respectively. The binary variable $N_{l,s,h,i}$ denotes whether the power $P_{l,s,h}$ is within the i-th segment, and its summation over i should be one. The continuous variable $\Delta P_{l,s,h,i}$ denotes the excess value of $P_{l,s,h}$ over the i-th segment. This results in the following set of equations:

$$P_{l,s,h} = \sum_{i=1}^{n_l} (a_{l,i} N_{l,s,h,i} + \Delta P_{l,s,h,i}) \quad \forall l, s, h \tag{1}$$

$$0 \leq \Delta P_{l,s,h,i} \leq (a_{l,i+1} - a_{l,i}) N_{l,s,h,i} \quad \forall l, s, h, i \tag{2}$$

$$\sum_{i=1}^{n_l} N_{l,s,h,i} = 1 \quad \forall l, s, h \tag{3}$$

For simplicity, we assume $\sum_l P_l^{max}$ equals the contracted power consumption in the long term energy contract[1]. Thus the smelter can sell energy to the market if its potlines are operating below P_l^{max}, i.e. consuming less than the contracted amount. Hence, the energy to sell $E_{s,h}$ is modeled as:

$$E_{s,h} = \sum_l (P_l^{max} - P_{l,s,h}) \qquad \forall s, h \tag{4}$$

The available spinning reserve is limited by the smelter's ability to further reduce its power consumption. Consequently, we require that the offered spinning reserve, once cleared in the market, should be available in every scenario. Thus the spinning reserve availability is modeled by

$$V_h \leq \min_s \sum_l (P_{l,s,h} - P_l^{min}) \qquad \forall h \tag{5}$$

which indicates that V_h needs to be less than the available amount in any of the considered scenarios.

As mentioned before, the thermal balance is the most critical issue in providing flexibility, and the potlines' temperature should be kept within a certain range to ensure high smelting efficiency as well as operation safety. This means that the energy consumption for every successive τ_l hours should be greater than E_l^τ, as in

$$\sum_{h'=h}^{h+\tau_l-1} (P_{l,s,h'} - V_{h'}) \geq E_l^\tau \qquad \forall l, s, h \tag{6}$$

where E_l^τ is the minimum input energy required for τ_l hours to sustain the temperature. The spinning reserve should be committed to last for at least one hour in most electricity markets. Note that (6) states that the temperature should also be sustained even if the spinning reserve is called and dispatched by the system operator. The impact of spinning reserve dispatch is considered in both (5) and (6), as these constraints are related to the potlines' operation safety.

Furthermore, there is daily aluminum production scheduled by a certain higher-level longer-horizon plant planning. It is also assumed that the plant has storage capability, meaning that there is some flexibility in terms of when the aluminum production takes place. Thus the total energy consumption during the operating day, which is proportional to the aluminum production quantity, is bounded according to

$$E_d^{min} \leq \sum_{h,l} P_{l,s,h} \leq E_d^{max} \qquad \forall s \tag{7}$$

where E_d^{min} and E_d^{max} are the daily minimum and maximum energy consumption, which is proportional to the minimum and maximum aluminum production amount.

In order to get a monotonous bidding curve, we require the following constraint to hold:

$$E_{s,h} - E_{s',h} \leq 0 \quad \forall h, s, s' : O_h(s) + 1 = O_h(s') \tag{8}$$

[1]Note that relaxing this assumption is straightforward.

where $O_h(s)$ denotes the order of the energy price for each scenario in hour h. The scenarios are ordered in each hour in an ascending order. For example, if s is the scenario with the lowest price in hour h, then $O_h(s)$ equals 1; if s' is the scenario with the highest price in hour h, then $O_h(s')$ equals the total number of scenarios.

The revenues from electricity market participation are calculated as

$$R = \sum_s p_s \cdot \sum_h \lambda_{s,h} (E_{s,h} + \rho_{h,s} V_h) \tag{9}$$

in which p_s stands for the probability of scenario s. Note that we do not consider the economics of the actual dispatch of spinning reserve due to the low dispatch rate. The economics analysis on spinning reserve dispatch should be conducted for longer-horizon scheduling, e.g. weekly scheduling or quarterly scheduling.

As mentioned before, the profit P from producing aluminum is approximated by piece-wise linear functions, as illustrated in Fig. 1, in which we assume that the marginal production profit is constant within each segment. The production profit is approximated by

$$P = \sum_s p_s \sum_h \sum_l \sum_{i=1}^{n_l} (c_{l,i} N_{l,s,h,i} + b_{l,i} \Delta P_{l,s,h,i}) \tag{10}$$

in which we assume that the potline l's marginal production profit is $b_{l,i}$ in its i-th segment, and the total value of production profit at the segment's left boundary (i.e. when $P_{l,s,h} = a_{l,i}$) is $c_{l,i}$. In this way, we can model the differences in smelting efficiency when the potline is operating at different loading levels. Generally, the production efficiency is higher when the loading level is higher, as the potline is originally designed to produce with full capacity.

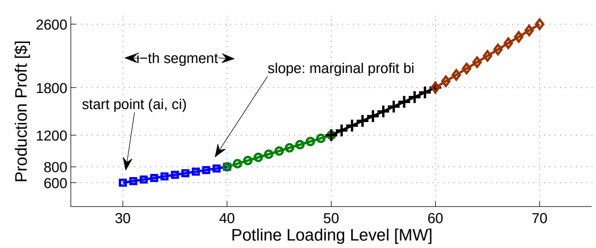


Fig. 1. The illustration for piece-wise linear approximation of the smelter's production profit.

The optimization objective of the daily bidding is to maximize the revenues from electricity market and the profit of producing aluminum, i.e.

$$\max \qquad R + P \tag{11}$$

Consequently, the overall problem is a mixed-integer linear programming problem.

IV. Case Study

A. Simulation Setup

We consider an aluminum smelting plant with two potlines. The potlines' parameters are listed in Table I. We approximate the production profit by 4 piece-wise linear segments, and the corresponding parameters are listed in Table II.

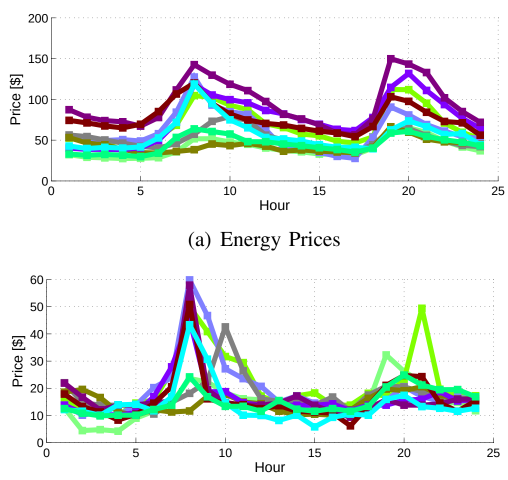
TABLE I
SMELTER PARAMETERS

l	$P_l^{min}[MW]$	$P_l^{max}[MW]$	$\tau_l[h]$	E_l^{τ} [MWh]
1	30	70	4	180
2	40	60	3	135

TABLE II
PIECEWISE LINEAR PARAMETERS FOR PRODUCTION PROFIT

$l = 1$	$\{a_i\}[MW]$	{30, 40, 50, 60, 70}
	$\{b_i\}[MW/\$]$	{56, 58, 60, 62}
	$\{c_i\}[\$]$	{1680, 2240, 2820, 3420}
$l = 2$	$\{a_i\}[MW]$	{40, 45, 50, 55, 60}
	$\{b_i\}[MW/\$]$	{66, 68, 70, 72}
	$\{c_i\}[\$]$	{2640, 2970, 3310, 3660}

The scheduling is carried on a daily basis and we focus on the day-ahead energy and spinning reserve markets. Price prediction techniques such as ARIMA and neural networks can be applied to generate price scenarios for the stochastic optimization problem. Scenario reduction method can be adopted to alleviate the computation burden of the mixed-integer programming by using a small number of representative scenarios. The price prediction and scenario reduction are not the focus of this paper, so in our case study we use historical MISO price curves (shown in Fig. 2) as our scenarios. The price curves correspond to the 10 days of 02/5/2014 to 02/14/2014. Energy and spinning reserve prices taken from the same day serve as one scenario, and are plotted with the same color. The probabilities of all scenarios are assumed to be equal.



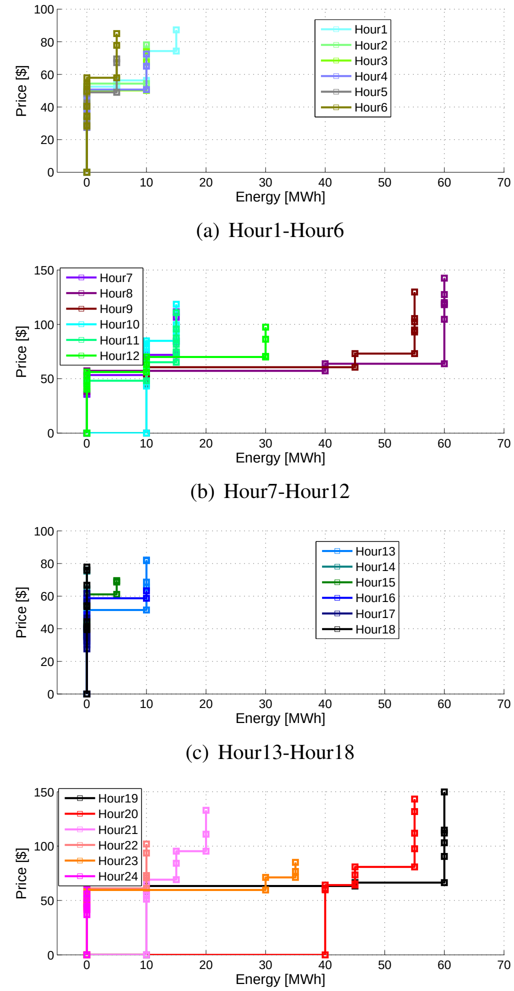
(a) Energy Prices

(b) Spinning Reserve Prices

Fig. 2. Price scenarios taken from MISO's historical data. The spinning reserve prices follow the trend of energy prices. The peak hours for both prices are around hour 8 and 20.

B. Simulation Results

The bidding model described in Section III is a mixed-integer linear programming problem. We solve this problem in MATLAB by the solver TOMLAB\CPLEX on a 64-bit Linux machine.



(a) Hour1-Hour6

(b) Hour7-Hour12

(c) Hour13-Hour18

(d) Hour19-Hour24

Fig. 3. The day-ahead energy bidding curves for each hour developed by the proposed bidding model.

The resulting hourly energy bidding curves given by our model are shown in Fig. 3. From the figures, we observe that the bidding curves are more conservative in terms of selling energy in hours 1-6 and hours 13-18, as the smelter asks for a very high price for selling very few energy. The smelter is even reluctant to sell any energy for hour 17 and 18. As seen in Fig. 2, the energy prices are relatively lower during these hours, so it is wise of the smelter to focus on producing aluminum and sell little energy during these hours. On the other hand, the bidding curves are more aggressive in hours 7-12 and hours 19-24, in which the smelter bids significant amounts of energy into the market. In particular, the smelter wants to sell around 55 MW of energy in hours 7, 8, 19, and 20. Comparing with Fig. 2, we observe that the energy prices during these hours are really high, so it makes sense for the smelter to be aggressive in selling energy.

The spinning reserve provision given by our model is displayed in Fig. 4. We can tell that the smelter is willing to provide more reserve then the reserve prices are higher. But the smelter provides little reserve at the exact peak hours 8, 9, 19 and 20. This can be explained by the fact that the smelter is focused on selling energy in these hours, because the

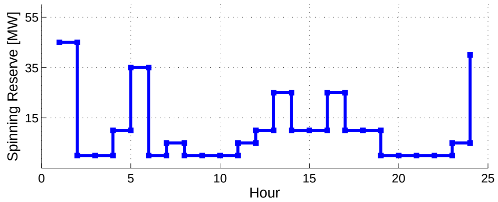


Fig. 4. Scheduled Spinning Reserve Provision

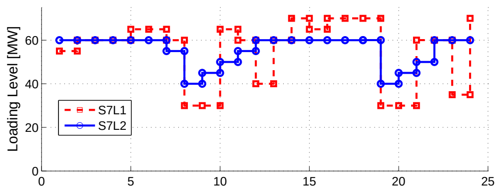


Fig. 5. Potline Power Consumption

energy prices are significantly higher than the spinning reserve prices. Thus, the potlines' loading levels during these peak hours are very low, leaving less space for providing spinning reserve. It should be kept in mind that the available spinning reserve capacity is upper bounded by the difference between the potline's current loading level and its minimum loading level: if the smelter lowers the potlines' loading levels to sell energy, then there is little spinning reserve capacity left. As discussed before, the smelter should bid this optimal spinning reserve schedule by asking a relatively low price.

Besides, we also analyze the power consumption of each potline. The power consumption in scenario 7 of both potlines are compared in Fig. 5. As we can see, potline 1 contributes more in providing flexibility while potline 2 concentrates more on smelting. This can be explained by the fact that the marginal production profit of potline 2 is higher than that of potline 1.

V. Conclusion

In this paper, we study the demand response for aluminum smelters that participate in both energy and spinning reserve day-ahead markets. We propose a stochastic optimization model that generates the day-ahead bidding strategy for the smelters. The inputs to the model are the smelting plant parameters and the price scenarios that represent future price trends. The output of the model are the energy bidding curves and the optimal spinning reserve provision as well as the power consumption levels of the potlines. The model is a mixed-integer linear programming problem which can be solved by commercial solvers very quickly. The effectiveness of the model is demonstrated by case studies. The model can take advantage of the future price trends and arrange the smelting activities to make profits from both electricity markets participation and aluminum production.

One of the future research directions is to incorporate price prediction techniques and scenario reduction methods to the model, and investigate the model by more case studies. In addition, we intend to integrate also regulation provision into the model.

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References

[1] M. Klobasa, "Analysis of demand response and wind integration in Germany's electricity market," *IET renewable power generation*, vol. 4, no. 1, pp. 55–63, 2010.

[2] B. J. Kirby, *Spinning reserve from responsive loads*. United States. Department of Energy, 2003.

[3] D. Todd, M. Caufield, B. Helms, A. P. Generating, I. M. Starke, B. Kirby, and J. Kueck, "Providing reliability services through demand response: A preliminary evaluation of the demand response capabilities of Alcoa Inc," *ORNL/TM*, vol. 233, 2008.

[4] M. Paulus and F. Borggrefe, "The potential of demand-side management in energy-intensive industries for electricity markets in Germany," *Applied Energy*, vol. 88, no. 2, pp. 432 – 441, 2011.

[5] T. Samad and S. Kiliccote, "Smart grid technologies and applications for the industrial sector," *Computers & Chemical Engineering*, vol. 47, pp. 76 – 84, 2012.

[6] D. Fabozzi, N. Thornhill, and B. Pal, "Frequency restoration reserve control scheme with participation of industrial loads," in *PowerTech*, 2013.

[7] R. Vujanic, S. Mariethoz, P. Goulart, and M. Morari, "Robust integer optimization and scheduling problems for large electricity consumers," in *American Control Conference (ACC)*, 2012, pp. 3108–3113.

[8] P. M. Castro, I. Harjunkoski, and I. E. Grossmann, "New continuous-time scheduling formulation for continuous plants under variable electricity cost," *Industrial & engineering chemistry research*, vol. 48, no. 14, pp. 6701–6714, 2009.

[9] S. Ashok, "Peak-load management in steel plants," *Applied Energy*, vol. 83, no. 5, pp. 413 – 424, 2006.

[10] K. Nolde and M. Morari, "Electrical load tracking scheduling of a steel plant," *Computers & Chemical Engineering*, vol. 34, no. 11, pp. 1899 – 1903, 2010.

[11] A. Hat and C. Artigues, "On electrical load tracking scheduling for a steel plant," *Computers & Chemical Engineering*, vol. 35, no. 12, pp. 3044 – 3047, 2011.

[12] P. M. Castro, L. Sun, and I. Harjunkoski, "Resourcetask network formulations for industrial demand side management of a steel plant," *Industrial & Engineering Chemistry Research*, vol. 52, no. 36, pp. 13 046–13 058, 2013.

[13] X. Zhang and G. Hug, "Optimal regulation provision by aluminum smelters," in *Power and Energy Society General Meeting*, 2014.

[14] G. Li, J. Shi, and X. Qu, "Modeling methods for genco bidding strategy optimization in the liberalized electricity spot market–a state-of-the-art review," *Energy*, vol. 36, no. 8, pp. 4686–4700, 2011.

[15] G. Steeger, L. Barroso, and S. Rebennack, "Optimal bidding strategies for hydro-electric producers: A literature survey," *IEEE Transactions on Power Systems*, vol. PP, no. 99, pp. 1–9, 2014.

[16] H. Pandžić, J. M. Morales, A. J. Conejo, and I. Kuzle, "Offering model for a virtual power plant based on stochastic programming," *Applied Energy*, vol. 105, pp. 282–292, 2013.

[17] X. Zhang, G. He, S. Lin, and W. Yang, "Economic dispatch considering volatile wind power generation with lower-semi-deviation risk measure," in *Electric Utility Deregulation and Restructuring and Power Technologies (DRPT)*, 2011, pp. 140–144.

[18] E. Aasgard, G. Andersen, S.-E. Fleten, and D. Haugstvedt, "Evaluating a stochastic-programming-based bidding model for a multireservoir system," *IEEE Transactions on Power Systems*, vol. PP, no. 99, pp. 1–10, 2014.

[19] E. Saiz-Marin, J. Garcia-Gonzalez, J. Barquin, and E. Lobato, "Economic assessment of the participation of wind generation in the secondary regulation market," *IEEE Transactions on Power Systems*, vol. 27, no. 2, pp. 866–874, 2012.

[20] E. Mashhour and S. M. Moghaddas-Tafreshi, "Bidding strategy of virtual power plant for participating in energy and spinning reserve marketspart i: Problem formulation," *IEEE Transactions on Power Systems*, vol. 26, no. 2, pp. 949–956, 2011.

[21] *Business Practices Manual: Energy and Operating Reserve Markets*, MISO, Feb 2013. [Online]. Available: https://www.misoenergy.org/Library/BusinessPracticesManuals/