# Hour-Ahead Offering Strategies in Electricity Market for Power Producers with Storage and Intermittent Supply

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## ABSTRACT

This paper proposes online offering strategies for a storage-assisted renewable power producer that participates in hour-ahead electricity market. The online strategy determines the offering price and volume, while no exact or stochastic future information is available in a time-coupled setting in the presence of the storage. The proposed online strategy achieves the best possible competitive ratio of $O(\log\theta)$, where $\theta$ is the ratio between the maximum and minimum clearing prices. Trace-driven experiments demonstrate that the proposed strategy achieves close-to-optimal performance.

## CCS CONCEPTS

•**Hardware** → **Smart grid;** •**Theory of computation** → *Online algorithms;* Scheduling algorithms;

## KEYWORDS

Storage-assisted renewable power producer; hour-ahead electricity market; offering strategy; competitive online algorithm design

**ACM Reference format:**
Lin Yang, Mohammad H. Hajiesmaili, Hanling Yi, and Minghua Chen. 2017. Hour-Ahead Offering Strategies in Electricity Market for Power Producers with Storage and Intermittent Supply. In *Proceedings of SIGMETRICS '17, June 5–9, 2017, Urbana-Champaign, IL, USA,* , 2 pages.
DOI: http://dx.doi.org/10.1145/3078505.3078543

## 1 INTRODUCTION

In this paper, we consider a scenario in which a Storage-assisted Renewable GENeration COmpany (sʀGENCO), like other traditional generation companies, participates in hour-ahead electricity market by submitting its offer. After receiving the offers, the market operator matches the offers with the bids from the demand-side and determines a clearing price. If the offering price of sʀGENCO is less than the clearing price, its offering volume is considered as the *commitment* to the market for the next hour. Fig. 1 demonstrates the scenario in this paper. This work focuses on designing profit maximizing offering strategies, i.e., the strategies that, with the goal of maximizing the profit, determine the offering price and volume, for sʀGENCO that participates in hour-ahead market.

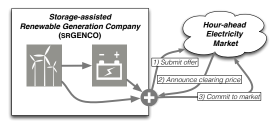


**Figure 1: The scenario**

Finding profit maximization offering strategy for a renewable producer without storage is nontrivial due to the inherent uncertainty of the renewables and dynamics in the market clearing price. In the presence of storage, the offering strategy is even more challenging because of the additional design space enabled by the storage. More specifically, sʀGENCO can use the storage absorb the uncertainty of renewables and to compensate for the slots that the renewable output cannot fulfill the commitment. However, the storage provides another economic advantage. That is, it can shift the energy through absorbing the renewable output during low price periods, and then discharging during high price periods. In this way, designing profit maximization offering strategy in the presence of storage comes with wider design space than those without the storage and potentially can bring more profit for sʀGENCO.

We formulate an optimization problem with the objective of maximizing the long-term profit of sʀGENCO. The future inputs to the problem, i.e., the renewable output and the clearing price, however, are unknown for sʀGENCO when submitting offer. This emphasizes the need for online solution design which is challenging, since the problem is coupled across time due to the evolution of the storage. We note that some similar problems have been studied in literature using stochastic optimization approaches [1], however, the solution approach in this paper is different since it has no assumption on the stochastic modeling of the future input. Our work could be considered as an extension of conversion problems [3].

**Contribution.** We propose sOffer, a simple online offering strategy, in which the offering strategy is designed using a piecewise exponential/constant function of the renewable output and the current storage level. The sOffer achieves the best possible competitive ratio of $O(\log\theta)$, where $\theta$ is the ratio between the maximum and minimum clearing prices. We refer to the full version of this paper [4] for detailed explanation.

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*SIGMETRICS '17, June 5–9, 2017, Urbana-Champaign, IL, USA*
 ACM ISBN 978-1-4503-5032-7/17/06.
DOI: http://dx.doi.org/10.1145/3078505.3078543

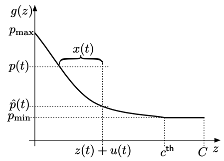


**Figure 2: Calculating $x(t)$ when $p(t) > \hat{p}(t)$.**

## 2 MODEL AND PROBLEM FORMULATION

We consider a time-slotted model, such that the time horizon $T$ is chopped into multiple slots with equal length, e.g., 1 hour. Shortly before slot $t$, srGENCO along with other participants submits its offer, for the next slot. We assume that srGENCO knows the values of market clearing price $p_{\min} \le p(t) \le p_{\max}$ and renewable output $u(t) \ge 0$ for the coming slot. Extensions to the case in which neither clearing price nor renewable output is not known is given in [4]. Different from [1], we do not have any assumptions on the stochastic modeling of clearing price and renewable output beyond the coming slot. Since it is assumed that the clearing price is known, by offering strategy we mean the way that srGENCO determines its offering (commitment) volume, denoted as $x(t) \ge 0$.

**Storage Model:** We denote the maximum capacity of storage system of srGENCO by $C$ and let $\rho_c$ and $\rho_d$ be its maximum charging and discharge rates, respectively. In addition, let $z(t) \in [0, C]$ be the storage level at the *beginning* of slot $t$. Given the renewable output $u(t)$ and the commitment volume $x(t)$, the evolution of the storage level of srGENCO is given by

$$z(t+1) = \Big[z(t) + x_c(t) - x_d(t)\Big]_{\mathcal{C}},$$

where $x_c(t) = \min\left\{\rho_c, \left[u(t) - x(t)\right]^+\right\}$ and $x_d(t) = \min\left\{\rho_d, \left[x(t) - u(t)\right]^+\right\}$ are the charging and discharging amounts of the storage at slot $t$. Moreover, $[.]^+$ and $[.]_{\mathcal{C}}$ define the projections onto the positive orthant and set $\mathcal{C} = [0, C]$, respectively.

Now, we cast the simplified offering strategy problem sOSP as

$$\begin{aligned}
\text{sOSP} \quad \max \quad & \sum_{t \in \mathcal{T}} p(t)x(t) \\
\text{s.t.} \quad & x(t) \le \min\{z(t), \rho_d\} + u(t), \\
& z(t+1) = \Big[z(t) + x_c(t) - x_d(t)\Big]_{\mathcal{C}}, \\
\text{var}: \quad & x(t) \ge 0, t \in \mathcal{T},
\end{aligned}$$

where the first constraint ensures that the feasibility of offering amount. The second constraint involves the evolution of the storage.

## 3 ALGORITHM DESIGN

We design our algorithm following an *adaptive threshold-based* strategy, where the algorithm adaptively changes the offering volume based on the current storage level and the clearing price. The main idea is to construct a function $g(z) : [0, C] \to [p_{\min}, p_{\max}]$. The input to function $g(\cdot)$ is the aggregation of the incoming renewable supply $u(t)$ and the current storage level $z(t)$, projected into the capacity of the storage. Given function $g(z)$ the strategy works as follows. It first calculates $\hat{p}(t) = g(z^+(t))$ as the candidate offering price for $z^+(t) = \min\left[z(t) + \min\{u(t), \rho_c\}\right]_{\mathcal{C}}$ as the storage level after absorbing renewable output. Since srGENCO knows the cleating price $p(t)$ it can finds the offering volume $x(t)$ as follows:

$$x(t) = \begin{cases} [u(t) - \rho_c]^+, & \text{if } \hat{p}(t) > p(t), \\ z(t) + u(t) - \min\{c^{\text{th}}, z(t) + \rho_c\}, & \text{if } \hat{p}(t) = p(t) = p_{\min}, \\ z(t) + u(t) - \min\{\hat{g}^{-1}(p(t)), z(t) + \rho_c\}, & \text{if } \hat{p}(t) < p(t), \end{cases}$$

An illustration of how offering volume is calculated is shown in Fig. 2. The following theorem characterizes the optimal function $g(\cdot)$ that leads to the best possible competitive ratio, for sOffer as the strategy that determines the offering volume as above.

Theorem 3.1. *By setting $g(z)$ as*

$$g(z) = \begin{cases} p_{\min} e^{\frac{(c^{\text{th}} - z)c^{\text{th}}}{C(C - c^{\text{th}})}} & \text{if } z \le c^{\text{th}}, \\ p_{\min} & z \ge c^{\text{th}}. \end{cases} \tag{1}$$

*where $c^{\text{th}}$ is*

$$c^{\text{th}} = C - \frac{(2 + \log\theta)C - \sqrt{\log^2\theta + 4\log\theta}C}{2} > 0, \tag{2}$$

*and $\theta = p_{\max}/p_{\min}$. In addition,*

$$\textsc{cr}(\text{sOffer}) = \frac{(2 + \log\theta) + \sqrt{\log^2\theta + 4\log\theta}}{2}. \tag{3}$$

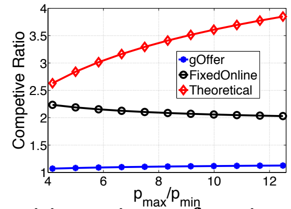


**Figure 3: Competitive ratio as a function of price volatility**

## 4 SIMULATIONS

Using data from PJM energy market, we evaluate the performance of our algorithm in Fig. 3. We measure the empirical competitive ratio of FixedOnline [2], that determines the offering volume based on a fixed threshold, and gOffer (the general version of sOffer where neither clearing price nor renewable output are known [4]), and show the theoretical competitive ratio. The result depicts that (i) gOffer is robust to price fluctuation; (ii) gOffer is superior to FixedOnline; (iii) it works much better than theoretical bound.

## ACKNOWLEDGMENT

Mohammad Hajiesmaili would like to thank Enrique Mallada for his helpful comments and financial support. The work presented in this paper was supported by the University Grants Committee of the Hong Kong Special Administrative Region, China (Theme-based Research Scheme Project No. T23-407/13-N).

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