Wind Power Producers' Costs And Associated Market Regulations: The Source of Wind Power Producers' Market Power

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Abstract

In this paper, I build a two-stage-multiple-hour model to analyze wind power producers' (WPPs) ability to manipulate price (ATMP) and market-power strategies in a sequentially structured electricity market. By exploring WPPs' cost structures and the dynamics that prices respond to wind-energy generation, the analyses demonstrate that WPPs can have significant ATMPs even though their marginal fuel costs are zero. Actually, the bidding rule regulating wind energy, which is different from the bidding rule regulating other technologies, provide WPPs a high flexibility to exercise their market power. The bidding rule, which allows WPPs separately determine their hourly generation, provide WPPs a particular strategy of utilizing wind-energy fluctuation and conventional generators' ramp constraints. My empirical simulation, which is based on data from Texas in 2012, demonstrates that WPPs already have ability to manipulate price in more than 900 hours in 2012. In some hours, they can inflate price by around 25%.

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1. Introduction

The increase of wind-energy penetration brings concerns about wind power producers' (WPPs) ability of to manipulate the price (ATMP). In Spain, annual wind-energy generation has already supplied over 20% of demands. In some other countries, the market share of wind energy in some hours can exceed 50%. In addition to clarifying traditional concerns about market power, studying the market-power issue of wind energy is critical in answering another important question in wind-energy market design: whether and when WPPs should be allowed to aggregately make bids in a electricity market. Actually, in order to control the growing wind-energy forecast error associated with increasing wind-energy penetration, researchers are discussing the business models that allow WPPs to aggregately bid into electricity markets[3, 16]. If I can demonstrate that WPPs do not have ATMP even if they collude in some hours, they should be allowed to aggregately bid in order to

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reduce forecast errors in those hours. Therefore, it is necessary to systematically analyze whether and when WPPs have unignorable ATMPs.

In this paper, I build a two-stage-multiple-hour model to examine WPPs ATMPs and strategies to exercise their market power. The two stages, which include the day-ahead (DA) stage and the real-time (RT) stage, simulate the sequential structure of electricity systems [17, 16]. I consider multiple hours in the model because I would like to examine WPPs' ATMPs and strategies when the WPPs and their GenCo competitors are regulated by different rules and have different bidding processes. In addition to theoretical analyses, I use data from the Electricity Reliable Commission of Texas (ERCOT) market in 2012 to measure WPPs ATMP when they aggregately bid.

This paper contributes a systematical analyzing framework to study the market-power issue of wind energy in literature. By using this analyzing framework, I provide conditions determining when a WPP has significant ATMPs even though their marginal fuel costs are zero. Because my framework considers multiple hours, I can examine how net-demand fluctuations and GenCos' ramp constraints impact WPPs' ATMPs and optimal strategies. To my best knowledge, the interaction between net-demand fluctuation with market-power strategies has not been systematically studied. Furthermore, by considering both the DA and RT markets, the framework built in this study can be also used to compare a WPP's ATMPs when it participates into different sequential markets. The empirical case demonstrates that this framework can be used in a real electricity market to monitor market-power issue of wind energy.

In fact, market power is the core issue for electricity-market regulation and has been deeply examined in a system mainly supplied by conventional electricity-generation companies(GenCos) [23, 24, 4, 10]. The electricity crisis in California demonstrated that market regulations, such as bidding rules and dispatch protocols, play essential rules to determine whether market players have mechanism to exercise their market power[6, 5, 11, 15, 22].

The California electricity crisis also inspired researchers to explore factors that determine GenCos' ATMPs and willingness to exercise market power[21, 13]. [13] explained why a GenCo can have ATMP in a electricity market supplied by multiple GenCos and developed a framework to measure GenCo's ATMP and willingness to exercise its market power. While the penetration of wind energy have been growing, researchers begin to focus on the interaction between wind-energy integration and market power [20, 12, 19, 2]. However, most these studies either focus on GenCos' market-power strategy when they own WPPs.

However, the models used to analyze GenCo's ATMP cannot be directly used to examine WPP's ATMP because WPPs and GenCos face to different grid-access and bidding rules when they exercise their market power.

GenCos and WPPs are regulated by different grid-access rules because they have different physical natures. Conventional technologies for electricity generation are controllable. Therefore, GenCos are required to provide supply curves in the DA market when they access to a power-grid system. In contrast, wind energy is intermittent. Therefore, the process that a WPP accesses into a power-grid system depends on how this power-grid system deals with the wind-energy uncertain cost. If the WPP is required to pay its own uncertain costs, it will be defined as a capacity resource (CR) and required to submit its hourly generation commitment in the DA market. If the WPP's generation is less than its DA commitment in an hour, it must purchase electricity from the RT market of that hour to compensate for its insufficient generation. If consumers or other market players are required to pay the costs associated with wind-energy uncertainty, the WPP is defined as a non-capacity resource (NCR) and can participate into the RT market directly. In the DA market, the SO reserves a market share for potential wind energy in each hour.

GenCos and WPPs are regulated by different bidding rules because they have different cost structures. Each GenCo is allowed to provide one supply curve per day because its fuel cost usually keeps the same in one day. In contrast, WPPs are forced to bid at at zero costs but allowed to separately determine hourly generations because wind energy has zero fuel costs and brings the whole system an uncertain cost that varies in different hours.

The above differences of market rules result in two consequences. First, WPPs do not necessarily have similar marginal fuel costs with their competitors. If a WPP is a CR, its marginal cost (MC) in the DA market is the marginal expected payment in the RT market rather than the marginal fuel cost. If a WPP is a NCR, it has a zero MC but competes with fringe GenCos in the RT market. It is necessary to explore factors that determine a WPP's competitors as well as ATMPs. Second, WPPs' strategies to exercise market power can be different from GenCos' while WPPs are required to determine hourly generation levels rather than provide one supply curve.

Thus, it is necessary to develop a research framework to examine WPP's ATMP and strategies to exercise their market power. However, WPPs' market power does not attract enough attentions because of wind energy's zero marginal fuel cost, which causes that policy makers usually assume wind-integration can always decrease price and ignore the potential market power issue of WPPs[14]. Only a few papers discuss WPPs' market-power strategies when they are regulated by the same rules with GenCos but do not discuss the impacts of special grid-access and bidding rules regulating WPPs[1, 18].

The remainder of the paper is organized as follows: the theocratical power market model is described in Section 2; in Section 3, I build a framework to analyze WPPs' ATMPs and develop index to measure WPPs' ATMPs; then, Section 5 includes discussion about how the special market regulations impact the WPPs' ATMP and strategies; Section 6 summarizes the impact of WPPs' market-power strategies on the fluctuation of wind energy; Section **??** includes the discussion about the scenario when WPPs are NRCs; the empirical study based on ERCOT 2012 data is included in to Section 8; lastly, in Section 9, I draw final conclusions.

2. Three-generator market model for theoretical analysis

2.1. Overview the basic structure of a electricity market in the U.S.

My market model include two stages. The first stage is called the day-ahead (DA) market, which occurs in one day ahead of the operation time. The second stage is called the real-time (RT) market, which occurs one hour ahead of the operation time. In the DA market, every GenCo submits its willingness-to-supply curve for the whole day to the SO. Simultaneously, consumers provide their aggregated demand level for each hour. According to the demand and supply curves, the SO integrally determines the hourly generation plans for the next day by solving an aggregated daily cost-minimization problem. If the demand or supply sides would like to change their contract made in the DA market, they can trade again in the RT market. In the RT market, the SO separately solves the market equilibriums hour by hour. In the DA market, the whole market know the the distribution function of wind energy in each hour. In the RT market, the wind-energy forecast is quite accurate. Thus in this research, I assume that the exact available wind energy is revealed in the RT market.

I first consider a simplified three-generator-two-hour model in which two GenCos and a WPP compete for supplying demands in two hours. In this model, a SO integrally calculates the market equilibrium of two hours in the DA market and separately calculates market equilibrium for each hour in the RT market. In this research, I use the superscript a (r) to represent factors in the DA (RT) market. In the first part of this research, I mainly focus on the situation in which WPPs are defined as CR. The situation in which WPPs are not CRs will be compared in later sections.

I do not consider the effects of demand uncertainties in this model because those effects have limited relationships with a WPP's market power. I also do not include the effects of transmission losses and limits because they do not essentially affect the conclusions. Because it is illegal and difficult for a WPP to collude with other market players, I in this paper examine the scenario that a strategic WPP competes with other GenCos.

2.2. The three-generator-two-hour (TGTH) model

In the TGTH model, the three generators include a coal-fired generator G_c, a gas-fired generator G_g, and a WPP w. For a GenCo, the cost function of G_i ($i \in \{c, g\}$) is

$$c_i(q_i) = \alpha_i q_i + \frac{\beta_i}{2} q_i^2. \tag{1}$$

I assume GenCos are price takers so that their biding curves are their marginal costs. I further assume that G_c has a limited maximum ramp rate r so that the difference between G_c's generation in two neighboring hours cannot exceed r.

I assume that the demands are inelastic and use L_j to denote the total demand in hour j. For hour j, there will be W_j MWhs wind energy available. In the DA market, the WPP knows the distribution of W_j, which is a truncated normal distribution between 0 and installed wine-energy capacity. The wind distribution in hour j has the mean $E[W_j]$ and standard deviation σ_j. To simulate the market structure when the WPP is defined as a CR, I assume that the SO requires the WPP to submit its hourly DA commitment q_{wj}^a separately with zero cost. In contrast, a GenCo is required to provide one marginal-cost curve (MC) for both hours.

If the WPP commits to produce q_{wj}^a in hour j in the DA market, I call $L_j - q_{wj}^a$ as the net load in hour j. I first examine the situation that the WPP's commitments result in a ramp up of the net load, which indicates that $L_1 - q_{w1}^a$ is less than $L_2 - q_{w2}^a$. I refer to this situation as that the net demand is ramping up. The analysis of the situation that the net demand is ramping down is symmetric.

In the DA market, the SO will integrally determine the generation plan for both hours according to GenCos' MCs and the WPP's commitments. Then, the market equilibrium

$\{q_{ij}^{a*}\}$ $(i \in \{c, g\})$ is solved from the following cost minimization problem.

$$\begin{aligned} \min_{q_{cj}^a, q_{gj}^a} \quad & \sum_{j=1}^{2} c_{cj}(q_{cj}^a) + c_{gj}(q_{gj}^a) \\ \text{s.t.} \quad & q_{cj}^a + q_{gj}^a \geq L_j - q_{wj}^a \qquad \text{j = 1, 2} \\ & -r \leq q_{c1}^a - q_{c2}^a \leq r. \end{aligned} \tag{2}$$

In the RT market of hour j, the WPP must procure electricity from GenCos if its generation is less than its DA commitment.The equilibrium of the RT market for hour j is solved by the SO from the following problems.

$$\min_{q_{cj}^r, q_{gj}^r} \; c_{cj}(q_{cj}^{a*} + q_{cj}^r) + c_{gj}(q_{gj}^{a*} + q_{gj}^r). \tag{3}$$

In hour 2, the optimization problem (3) must satisfy G_c's ramp constrain.

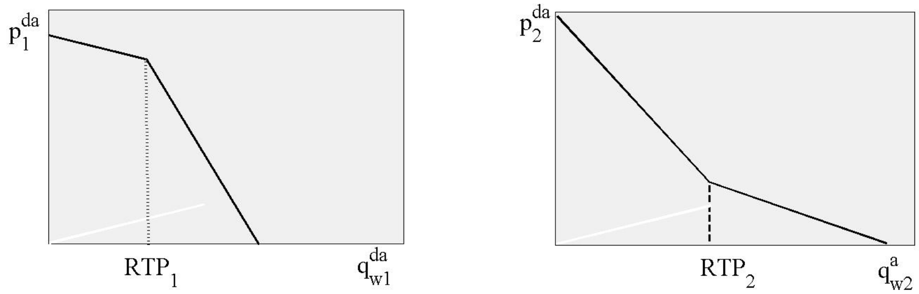
$$|(q_{c1}^a + q_{c1}^r) - (q_{c2}^a + q_{c2}^r)| \leq r. \tag{4}$$

In the DA market, if G_c's ramp constraint is binding, prices in both hours are affected. However, if G_c's ramp constraint is binding in the RT market, only the equilibrium in hour 2 is affected.

3. Measure the WPP's ability to manipulate price (ATMP) by strategically reducing commitment levels

3.1. Price response to the WPP's commitment

A WPP can manipulate the market price by strategically reducing its commitment levels in the DA market. In the Appendix, I calculate the market equilibriums in the DA and RT markets. When GenCos compete rather than collude with the WPP, market prices are still functions of the WPP's commitments. According to Eq.(2) , a WPP's commitment pair (q_{w1}^a, q_{w2}^a) will lead to corresponding market equilibriums, which include the DA price



(a) Hour 1 (b) Hour 2

Figure 1: The WPP's residual inverse demand (RID) curves in the three-generator case

p_j^a of hour j. Therefore, the price p_j^a is a function of the pair (q_{w1}^a, q_{w2}^a). In my TGTH model, the prices are

$$p_1^a = \begin{cases} \phi_1' - \frac{\beta_g\beta_c}{\beta_g+\beta_c} q_{w1}^a, \text{if } q_{w1}^a \le RTP_1; \\ \phi_1 + \frac{\beta_g^2}{2(\beta_c+\beta_g)} q_{w2}^a - \frac{\beta_g(2\beta_c+\beta_g)}{2(\beta_c+\beta_g)} q_{w1}^a \text{ if } q_{w1}^a \ge RTP_1. \end{cases} \tag{5}$$

and

$$p_2^a = \begin{cases} \phi_2' - \frac{\beta_g\beta_c}{\beta_g+\beta_c} q_{w2}^a, \text{if } q_{w2}^a \ge RTP_2; \\ \phi_2 + \frac{\beta_g^2}{2(\beta_c+\beta_g)} q_{w1}^a - \frac{\beta_g(2\beta_c+\beta_g)}{2(\beta_c+\beta_g)} q_{w2}^a \text{ if } q_{w2}^a \le RTP_2. \end{cases} \tag{6}$$

Here RTP_1 and RTP_2 are the tipping points that determine whether G_c's generation is limited by its own ramp rate. The tipping points are

$$RTP_1 = [L_1 - L_2 + q_{w2}^a + \frac{\beta_c + \beta_g}{\beta_g} r]_+ \tag{7}$$

and

$$RTP_2 = [L_2 - L_1 + q_{w1}^a - \frac{\beta_c + \beta_g}{\beta_g} r]_+. \tag{8}$$

I call p_j^a, which is a function of (q_{w1}^a, q_{w2}^a), the WPP's residual inverse demand curve in hour j and refer to it as RID_j. I conceptually show the residual inverse demand (RID) curves in Fig. 1

The two figures demonstrate that price will increase when the WPP reduces its commitment even if GenCos compete rather than collude with the WPP. In fact, the price increases because GenCos' marginal costs increase when they generate more to compensate for the WPP's commitment reduction.

RID curves have a piece-wise characteristic, which reflects that GenCos' ramp rates can change the relationship between market price and the WPP's commitment. For example, in Fig. 1(b), the piece on the left of the RTP_2 has a steep slop, but the right piece has a flat slope. The slopes are different because G_c's ramp constraint is tight once $q^a_{w2} < RTP_2$, which leads the price to be more sensitive to WPP's commitment change. According to Eq. (6), one less unit commitment from the WPP inflates the price by $\frac{\beta_g\beta_c}{\beta_g+\beta_c}q^a_{wj} + \frac{\beta_g^2}{2(\beta_c+\beta_g)}$ when $q^a_{w2} < RTP_2$. In contrast, one less unit commitment from the WPP only inflates the price by $\frac{\beta_g\beta_c}{\beta_g+\beta_c}q^a_{wj}$ when $q^a_{w2} \geq RTP_2$.

The effects of GenCos' ramp rates on the price's sensitivity to the WPP's commitment varies in different hours. In both two hours, price increase while the WPP reduces its commitment. However, the price increase slows down in hour 1 but speeds up in hour 2. This is because a large WPP's commitment in hour 1 will tighten GenCos' ramp constraints. In contrast, in hour 2 when net demand is high, a low WPP's commitment can tighten GenCos' ramp constraints tight. Therefore, I have the following theorem.

Theorem 3.1. *In an hour with a high net demand, the market price becomes more sensitive to WPPs' commitments while WPPs reduce their commitments. In an hour with a low net demand, the market price becomes less sensitive to WPPs' commitments while WPPs reduce their commitments.*

3.2. Index to measure the WPP's ATMP

I measure the WPP's ATMP by using the slope of RID_j between $\hat{q}^a_{wj}$, the WPP's commitment as a price taker, and q^{a*}_{wj}, the WPP's commitment as a market power. I use the slope between these two points because a rational WPP's commitment will not exceed its price-taker commitment level or be lower than its market-power level. Then, I define the following index to measure the WPP's ATMP.

Definition I define the inverse elasticity of the RID in period j as

$$\eta_j^a = \frac{p_j^a(\hat{q}_{wj}^a) - p_j^a(q_{wj}^{a*})}{\hat{q}_{wj}^a)} / \frac{\hat{q}_{wj}^a - p_j^a(q_{wj}^{a*}}{\hat{q}_{wj}^a}. \tag{9}$$

The WPP has a high ATMP when η_j is large

I would like to particularly emphasize that, in contrast with GenCos' ATMPs, a WPP's ATMP is contingent to how the WPP optimizes its own profit. A WPP can separately determine its market-power commitments by maximizing its total expected profit of each hour. Or, the WPP can integrally determine several hours' market-power commitments by maximizing its total expected profits of these hours. how many hours the WPP integrally maximize its profits determines this WPP's market-power commitment level q_{wj}^{a*} in hour j. Therefore, the value of η_j^a also depends on how the WPP selects its market-power commitment. Thus, **I use η_{jN}^a to represent the WPP's ATMP when WPP determine its market-power commitment by integrally maximizing N hours' profit.**

4. Factors determine when the WPP has significant ATMP

4.1. The WPP's marginal commitment cost

When defined as RC, the WPP faces a marginal commitment cost (MCC) in each hour that reflects the expected penalty when this WPP commits one more unit of generation in the DA market. I use mcc_j to represent the WPP's MCC in hour j. Because a WPP's ATMP in hour j is the average slope of RID_j between q_{wj}^{a*} and $\hat{q}_{wj}^a$, which are determined by mcc_j, the WPP's MCC has decisive impacts on the sam WPP's ATMP (Fig. 2). However, the WPP's MCC varies by hour. Thus, the WPP's ATMP in each hour of the same day can differ significantly.

The WPP's MCC impacts the ATMP by determining the WPP's competitors in each hour. η_j is the average slope of RID_j between q_{wj}^{a*} and $\hat{q}_{wj}^a$. Therefore, when a WPP reduces its commitment from $\hat{q}_{wj}^a$ to q_{wj}^{a*}, the WPP competes with GenCos whose marginal costs are in between $mcc_j(q_{wj}^{a*})$ and $mcc_j(\hat{q}_{wj}^a)$. And the price inflation reflects the change of

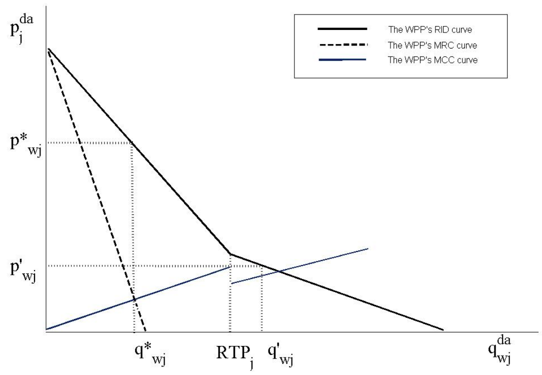


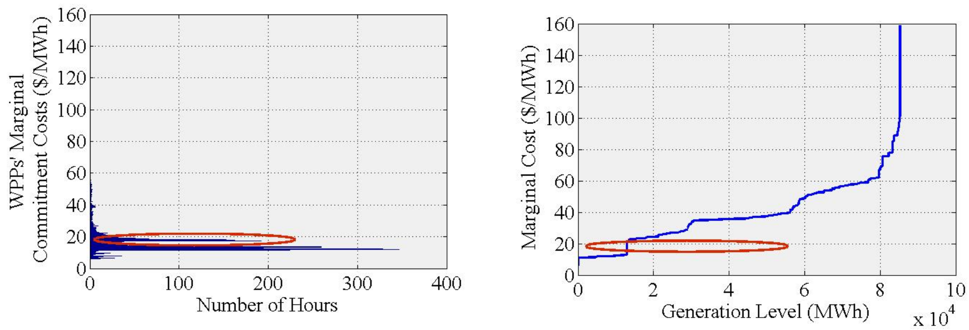
Figure 2: The WPP's MCC and ATMP in hour 2

these GenCos' marginal costs. Thus, The WPP has a high ATMP in hour j when GenCos, whose marginal costs is in between $mcc_j(q^{a*}_{wj})$ and $mcc_j(\hat{q}^{a}_{wj})$, has steep-slope supply curves. Then, I have the following theorem.

Theorem 4.1. *A WPP has a high ATMP in hour j if GenCos whose supply curves are in between $mcc_j(q^{a*}_{wj})$ and $mcc_j(\hat{q}^{a}_{wj})$ have steep slopes.*

Again, I would like to emphasize, the WPP's ATMP varies in different hours because the WPP's MCC varies in different hours.

In fact, in contrast with GenCos, which mostly have high ATMPs when demand is quite high, WPPs can have high ATMPs even if the demand is moderate. For example, WPPs can have high ATMPs in some hours when demands are moderate but marginal GenCos change from coal-fired GenCos to gas-fired GenCos. I calculate the average of WPPs' hourly price-taker MCC $mcc_j(q^{a*}_{wj})$ and market-power MCC $mcc_j(\hat{q}^{a}_{wj})$ in ERCOT 2012 and plot the histogram in Fig. 3(a). In Fig. 3(b), I plot the aggregated marginal-cost curve of GenCos in the ERCOT in 2012. By comparing the two figures, I suggest that WPPs can have high ATMPs in hours when their average MCCs are around 20 $/MWh. In these hours, the supply curve, which reflect the marginal costs of WPPs' GenCos, sharply increases. In contrast, GenCos whose marginal costs are around 20 $/MWh usually have very limited ATMPs because they can only provide one supply curve in each day. If they strategically inflate cost curves for the hour when they are fringe generators, they will not be dispatched



(a) Histogram of WPPs' Hourly MCCs in ERCOT 2012

(b) Aggregated GenCos' Marginal Cost Curves in ERCOT 2012

in other hours when the demand is low. When the demand is relatively high, their bidding curves have little influence on the price. **Therefore, WPPs have more opportunity to exercise market power because they are allowed determine hourly generation levels.**

Actually, because the WPPs's MCCs varies by hours, they are allowed to separately determine their hourly generation levels rather than provide daily supply curve. A WPP's MCC is determined by wind-energy distribution and MCs of GenCos who can provide electricity market in the RT market. Additionally, a WPP's MCC in an hour can be impacted by its own generations and demands in neighboring hour's because of the effects of GenCos' ramp constraints. In the Appendix, I detailed discuss the MCC of the WPP in my TGTH model and summarize the analyses in the following theorem.

Theorem 4.2. *A WPP's MCC is a increase function of its DA commitment level in the same hour. In a high net-demand hour, the WPP's MCC is sensitive to its own DA commitment in the same hour if*

- *its competitors have limited ramp rates,*
- *or this WPP make a high commitment in a low-net-load neighboring hours when GenCos ramp constraints are binding.*

4.2. GenCos' ramp rates and market conditions in neighboring hours.

WPPs' ATMP in a high-net-demand hour can be significantly impacted by GenCos ramp rates and market conditions in neighboring low-net-demand hours. In my TGTH model, the WPP's ATMP in hour 2 is determined by the location of RTP_2 once RTP_2 falls in between q_{w2}^{a*} and $\hat{q}_{w2}^{a}$. According to Eq.(8), RTP_2 is a function of G_c's ramp rate r, demand in hour 1 L_1, and the WPP's commitment in hour 1 q_{w1}^a. Furthermore, these factors also impact q_{w2}^{a*} by determining the WPP's MCC in hour 2. Therefore, these three factors impact the WPP's ATMP.

GenCos's ramp rates impacts a WPP's ATMP by determining its RID and MCC curves. In fact, a WPP has a high ATMP when GenCos ramp rates are small. For example, in my TGTH model, G_c's ramp rate r impacts the WPP's ATMP in hour 2 by determining the value of RTP_2 and q_{w2}^{a*}. According to Eq.(8), RTP_2 is a decrease function of G_c's ramp rate r. Therefore, a decrease of r will increase the value of RTP_2. In contrast to the effect on RTP_2, the dynamic that r impacts q_{w2}^{a*} is complicated. Actually, a decrease of r raises both the WPP's RID and MCC curves. If the effect on the RID curve is stronger than that on the MCC curve, r's decrease raises q_{w2}^{a*}. Otherwise, r's decrease reduces q_{w2}^{a*}. However, in the Appendix, I demonstrate that the distance between q_{w2}^{a*} and RTP_j is always increasing while r is decreasing no matter how r impacts q_{w2}^{a*}. Consequently, r's decrease raises the value of η_2^a according to Eq.(9). The analyses for hour 1 is symmetric.

Because RTP_j impacts η_j and is determined by market conditions in neighboring hours, the WPP's ATMPs in hour j are impacted by these conditions including demand and the WPP's commitment level. For example, η_2 is impacted by L_1 and q_{w1}^a. Given the same L_2, a larger $L_1 - q_{w1}^a$ helps the WPP gain higher ATMP.

Actually, a decrease of L_1 raises the WPP's AEMP by rising the steep-slope piece of RIDC in hour 2. Consequently, both RTP_2 and q_{w2}^{a*} increase while L_1 is declining. Because RTP_2 increases more than q_{w2}^{a*} does, η_j^a increases with L_1.

Simultaneously, a increase of q_{w1}^a exacerbates the WPP's AEMP. Similar to the effect of increasing L_2, an increase of q_{w1}^a also raise the steep-slope piece of the RID curve in hour 2. Additionally, q_{w1}^a's increase also influences the WPP's MCC curve in hour 2. When q_{w1}^a is increasing, mcc_2 becomes less and less sensitive to q^a_{w2}. The aggregated effect of these two dynamics results in increases of RTP_2 and q^{a*}_{w2}. However, η^a_j sill increases because RTP_2 increases more than q^{a*}_{w2} does.

In the appendix, I mathematically demonstrate the above dynamics and have the following theorem.

Theorem 4.3. *Once the WPP's strategic commitment reduction causes GenCos generations to be limited by their ramp rates, the WPP has a high ATMP in the hours with high net demand if*

- *GenCos' ramp rates are small,*
- *the net-demand ramp is large,*
- *demands are low in hours with low net demands,*
- *or the WPP itself makes high generation commitments in hours with low net demands.*

5. WPP's strategy of utilizing fluctuations of net demands and GenCos' ramp rates

Compared with GenCos, WPPs have a particular strategy to manipulate the market price by utilizing fluctuations of net demands. By adopting this particular strategy, WPPs can inflate price higher but produce more when net-demand fluctuations are significant than when net-demand fluctuations are moderate. WPPs have this particular strategy because WPPs are allowed separately submit hourly commitment. In this section, I analyze this particular strategy and its impacts on the forecasted wind-energy fluctuations.

In my TGTH model, the WPP can gain a higher profit by integrally maximizing profits of the two neighboring hours when G_c's ramp rate can be tightened because of the fluctuation of the net demands. In the above analyses, I demonstrate that the WPP's AEMP in hour 2 can be impacted by the WPP's own commitment in hour 1 q^a_{w1}. Therefore, if WPPs integrally determines its optimal commitments in the two hours, the WPP can gain market-power rents by utilizing G_c's ramp rate to enhance it own AEMP in hour 2. By utilizing G_c's ramp rate, the WPP can generate more in hour 1 to enhance the WPP's

ATMP in hour 2. Consequently, the WPP in hour 2 can inflate price to a higher level but reduce less commitment level than when the WPP separately maximize its hourly profit.

In fact, if the WPP in the TGTH model integrally determines its commitments in the two hours, the WPP's profit maximization problem is,

$$\begin{aligned} &\max_{q_{wj}^a, q_{wj}^r} \; p_1^a q_{w1}^a + p_2^a q_{w2}^a + \tau(w_1 + w_2) - E[p_1^r(q_{w1}^a - q_{w1}^r) + p_2^r(q_{w2}^a - q_{w2}^r)] \\ &\text{s.t. } q_{wj}^r \le W_j. \end{aligned} \tag{10}$$

Here, τ is the subsidy for the WPP's per-unit generation. Therefore, the WPP's market-power commitments in the two hours are solved from

$$\tau + p_1^a + \frac{\partial p_1^a}{\partial q_{w1}^a} q_{w1}^a + \frac{\partial p_2^a}{\partial q_{w1}^a} q_{w2}^a \mathbf{1}(q_{w2}^a < RTP_2) = mcc_1, \tag{11}$$

$$\tau + p_2^a + \frac{\partial p_2^a}{\partial q_{w2}^a} q_{w2}^a + \frac{\partial p_1^a}{\partial q_{w2}^a} q_{w1}^a \mathbf{1}(q_{w1}^a > RTP_1) = mcc_2, \tag{12}$$

From these two conditions, I can solve for f_{21}, the WPP's best response function of hour 2 that reflect how q_{w2}^{a*} respond to q_{w1}^a. Similarly, I can solve for f_{12}, the WPP's best response function of hour 1 to its own commitment in hour 2.

In fact, the WPP's marginal benefit curve in each hour includes two parts. One part is the marginal benefit from manipulating price in the current hour. The other is the marginal benefit from manipulating the neighboring hour's price. For example, on the left-hand side of Eq. (11), which is the WPP's marginal benefit curve in hour 1, $\tau + p_1^a + \frac{\partial p_1^a}{\partial q_{w1}^a} q_{w1}^a$ is the marginal benefit from using q_{w1}^a to manipulate p_2^a. There is an additional term $\frac{p_2^a}{q_{w1}^a}$ that reflects the WPP's marginal benefit from using q_{w1}^a to manipulate p_2^a. Because $\frac{p_2^a}{q_{w1}^a}$ is positive according to Eq.(6), the WPP has incentive to commit more in hour 1 than when the WPP separately determines its hourly optimal strategy.

The economical explanation of the above dynamic is that the WPP has a incentive to raise q_{w1}^a in exchange for a high profit in hour 2 if the WPP integrally determine its strategies in the two hours. A increase of q_{w1}^a has three effects: inflating the DA price in hour 2, enlarging the WPP's ATMP in hour 2, and decreasing the WPP's MCC in hour 2. All three effects incentivize the WPP to generate more but keep the price in hour 2 at a high level. Therefore, I have the following theorem.

Theorem 5.1. *If GenCos' ramp rates limit their generations in two hours while WPPs exercise their market power, WPPs have incentives to make more generation commitment in low-net-demand hours when they integrally determine strategies in these two hours than when they separately determine the hourly strategies. WPPs make more commitment in low-net-demand hours to in exchange for a higher ATMP and lower MCC in high-net-demand hours. I call this effects the* ***ramping rate's rebound(R3) effect****.*

I would like to emphasize that R3 effect can occur both in the scenarios when net load is ramping up and the scenario when net load is ramping down. When the net load is ramping up, the WPP will make high commitment in low-net-demand hour in exchange for higher profit in the following hours. In contrast, when the net load is ramping down, the WPP will make high commitment in low-net-demand hour in exchange for high provit in the previous hours.

6. WPP's strategic behavior and wind-energy fluctuation

While net-demand fluctuations determines WPPs' strategies explained in the last section, WPPs' strategies also impact net-demand fluctuations. Once wind-energy penetration is significant, wind-energy fluctuations unignorably affect the extent of net-demand fluctuations. However, the extends of wind-energy fluctuation are determined by strategies adopted by WPPs for DA-commitment making. Therefore, net-demand fluctuations will be sensitive to strategies adopted by WPPs. In particular, net-demand fluctuations are different when WPPs separately determine commitments of each hour from when WPPs integrally determine commitments of several hours.

For example, wind-energy fluctuation, as well as net-demand fluctuation, is different when the WPP in the TGTH model choose different strategies. In Theorem 5.1, I demonstrate that R3 effect causes the WPP to make a high generation commitment in hour 1 when the WPP integrally determine strategies in two hours than when the WPP separately determines its hour strategy. The R3 effect also impacts the WPP's commitment in hour 2 and the wind-energy fluctuation. I summarize the impacts in the following theorem.

Theorem 6.1. *If the WPP integrally determine its strategies in two hours rather than separately determine hourly strategies, net-demand-energy fluctuation is aggravated if*

$$\frac{\partial q_{w2}^{a*}}{\partial p_2^a}\frac{\partial p_2^a}{\partial q_{w1}^a} + \frac{\partial q_{w2}^{a*}}{\partial mcc_2}\frac{\partial mcc_2}{\partial q_{w1}^a} < 1. \tag{13}$$

Otherwise, the net-demand-energy fluctuation keeps the same or is moderated.

The proof of the above theorem is also the economical explanation of the condition Eq. (13). The first term of the left-hand side of Eq. (13) is the increase of q_{w2}^{a*} that respond to p_2^a's change of caused by one-unit more q_{w1}^a. The second term is the increase of q_{w2}^{a*} that respond to mcc_2's change caused by one-unit more q_{w1}^a. If the integrated effects of increasing q_{w1}^a by one-more unit causes q_{w2}^{a*} to increase by less than one unit, the wind-energy fluctuation will be aggravated because the value of $q_{w1}^a - q_{w2}^{a*}$ enlarges.

In fact, the q_{w2}^{a*}'s sensitivity to q_{w1}^a depends on competitors' supply curves and the joint distribution of wind energy in the two hours according to Eq. (5) and Eq. (B.1). In fact, q_{w1}^a's growth stimulates q_{w2}^{a*} to increase more if the ratio β_g/β_c has a larger value. **Therefore, if the slow-ramping GenCos have much lower costs than fast-ramping GenCos, R3 effect can shrink the wind-energy fluctuations**. However, if $E[W_1 - W_2]$ is large, increasing q_{w1}^a have small effect of decreasing mcc_j. Consequently, q_{w2}^{a*}'s growth is small when R3 occurs. **Therefore, R3 can enlarge the wind-energy fluctuations when the wind-energy forecasts has already significantly fluctuated**.

7. WPPs' market power when they are NRC

If the WPP is defined as NRC, their ATMPs can be analyzed by the same framework explained above. However, there are two essential differences. First, the WPP's ATMP is determined by demands and wind-energy forecast rather than its MC. In fact, the WPP can participate in the RT market and has zero MCs, and the SO will reserve market shares for it in the DA market. The low-cost GenCos will be dispatched in the DA market to balance the net load, which is the forecast wind energy subtracted from the demand. The fringe GenCos will be used in the RT market if the WPP's generation is less than the reserved market share. Therefore, the fring GenCos' MCs determine the slopes of WPP's RIPs and marginal-benefit (MB) curves. Because WPP's marginal cost is zero, the RIPs determines the value of eta_j. Actually, all characteristics of RIPs, which include the slope of each piece and the location of tipping point, are determined by demands, wind-energy forecasts, fringe GenCos's ramp rates and MCs. In addition, the demand and wind-energy forecast determine which GenCos are fringe in an hour. Therefore, the demand level and wind-energy forecasts determine the WPP's ATMP.

In addition, the SO separately calculate RT market equilibrium for each hour in the RT market in contrast with integrally calculate market equilibrium for all hours in the DA market. Therefore, The R3 effect will occur only when the net load in the RT market is ramping up.

8. WPPs' market power in the ERCOT market in 2012

In order to examine WPPs' ATMPs in a real electricity market by using my analyzing framework presented in this paper, I calculated the ATMPS of the WPPs in the ERCOT market in 2012 if the WPPs are aggregately bid in the RT market. I assume WPPs separately optimal their hourly profits. In the DA market, the SO will determine the generation plan for the next 24 hours that starts from 12 am the next day and reserve market shares for WPPs according to hourly wind-energy forecast. I assume GenCos are price takers and their marginal generation costs are their heat rates times fuel costs. In the RT market, the SO separately solves the market equilibriums hour by hour. In this study, I ignore the effects of demand forecast error and assume hourly demand is inelastic and known in the DA market.

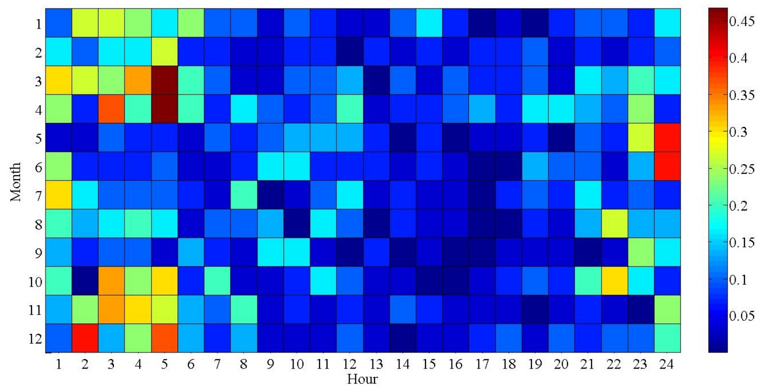


Figure 3: The average probability of the WPPs have ability to manipulate the prices

The data of hourly demands and wind-energy forecasts are provided by ERCOT[9]. The data include wind-energy hourly generation, the DA wind energy forecast, and 20% quantiles of forecast errors. The fuel-price data is from the Energy Information Agency (EIA)[7]. The technological features of the generators are from the Emissions & Generation Resource Integrated Database (eGRID), issued by the United States Environmental Protection Agency (EPA)[8]. The eGRID database provides the heat rates (MMBtu/MWh) and the maximum generation capacities of 235 generators in the ERCOT

The calculation results demonstrate that WPPs already have had significant ATMPs in some hours even at the 2012's penetration levels in ERCOT, which is around 9% of the total electricity generation. In 2012, there are more than 900 hours in which the WPPs have ATMPs that are greater than zero. In 93 hours, 1 MWh's decrease of WPP's generation can result in nearly 9$/MWh, which is around 25% of the DA price level. In order to examine when WPPs have high potential to have ATMPs, I also calculate the monthly probability of each hour in which the WPPs have ATMPs. The results are summarized in Figure 3. I observed that hours that WPPs have ATMPs concentrate in some particular period such as late night and early morning. The WPPs have market power in these periods because GenCos have limited ramp rates and wind-energy fluctuations are significant.

9. Conclusions

In this paper, I build a two-stage-multiple-hour model to analyze wind power producers' (WPPs) ability to manipulate price and market-power strategies in a sequentially structured electricity market. By separately examining two scenarios when WPPs participate in the day-ahead and real-time markets, I clarify the cost structure of WPPs and explore which factors determine WPPs' ATMPs. I examine when WPPs have significant ATMPs. The analyses demonstrate that WPPs can have significant ATMPs even though their marginal fuel costs are zero. Furthermore, the current bidding regulation that allows WPPs to separately determine their hourly generations provide WPPs more flexibility to exercise their market power. Because of this regulation, WPPs can gain high ATMPs in peak-demand hours by adjusting their generation in low-demand hours. Furthermore, WPPs can utilize conventional generators' ramp constraints to exercise their market power so that they can inflate prices higher and produce more electricity than suppliers who are only allowed to provide one supply curve per day in the day-ahead market. My empirical simulation based on data from Texas in 2012 demonstrates that WPPs already have ATMPs in over 900 hours.

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10. Appendix

Appendix A. Market equilibrium of the TGTH model

In DA, the generators submit their bid curves to the SO. Because I focus on the market power of wind, I assume convention generators are truthful in their bids and submits their marginal cost curves. If the WPP is defined as CR, its DA commitment level in hour j is q^a_{wj}.

By solving (2), the day-ahead dispatch is:

$$q^a_{c1} = \begin{cases} \frac{\alpha_g-\alpha_c}{\beta_c} + \frac{\beta_g}{\beta_g+\beta_c}(L_1 - q^a_{w1} - \frac{\alpha_g-\alpha_c}{\beta_c}), \\ \text{if } |q^a_{c1} - q^a_{c2}| < r; \\ \frac{\beta_g(L_1-q^a_{w1}+L_2-q^a_{w2})+2(\alpha_g-\alpha_c)}{2(\beta_c+\beta_g)} \mp \frac{r}{2}, \\ \text{if } q^a_{c1} - q^a_{c2} = \mp r. \end{cases} \tag{A.1}$$

$$q^a_{c2} = \begin{cases} \frac{\alpha_g-\alpha_c}{\beta_c} + \frac{\beta_g}{\beta_g+\beta_c}(L_2 - q^a_{w2} - \frac{\alpha_g-\alpha_c}{\beta_c}), \\ \text{if } |q^a_{c1} - q^a_{c2}| < r; \\ \frac{\beta_g(L_1-q^a_{w1}+L_2-q^a_{w2})+2(\alpha_g-\alpha_c)}{2(\beta_c+\beta_g)} \pm \frac{r}{2}, \\ \text{if } q^a_{c1} - q^a_{c2} = \mp r. \end{cases} \tag{A.2}$$

$$q^a_{g1} = \begin{cases} \frac{\beta_c}{\beta_g+\beta_c}(L_1 - q^a_{w1} - \frac{\alpha_g-\alpha_c}{\beta_c}), \\ \text{if } |q^a_{c1} - q^a_{c2}| < r; \\ \frac{(2\beta_c+\beta_g)(L_1-q^a_{w1})-\beta_g(L_2-q^a_{w2})-2(\alpha_g-\alpha_c)}{2(\beta_c+\beta_g)} \pm \frac{r}{2}, \\ \text{if } q^a_{c1} - q^a_{c2} = \mp r. \end{cases} \tag{A.3}$$

$$q_{g2}^a = \begin{cases} \frac{\beta_c}{\beta_g+\beta_c}(L_2 - q_{w2}^a - \frac{\alpha_g-\alpha_c}{\beta_c}), \\ \text{ if } |q_{c1}^a - q_{c2}^a| < r; \\ \frac{(2\beta_c+\beta_g)(L_2-q_{w2}^a)-\beta_g(L_1-q_{w1}^a)-2(\alpha_g-\alpha_c)}{2(\beta_c+\beta_g)} \mp \frac{r}{2}, \\ \text{ if } q_{c1}^a - q_{c2}^a = \mp r, \end{cases} \tag{A.4}$$

If the WPP is NCR, the SO will determine the DA market equlibrium according to expected wind-energy level $E[W_j]$. Therefore, I can get the day-ahead dispatch by replacing q_{wj}^a by $E[W_j]$ in Eq. (A.1) Eq. (A.4). According to the dispach, I can get the market-clearing price as Eq. (5) and Eq. (6)

Given WPP's generation level W_j in hour j, the optimal RT dispatch strategy for period 1 is

$$\begin{aligned} q_{c1}^r = & \frac{\beta_g}{\beta_g+\beta_c}(q_{w1}^a - W_1) + (\frac{1}{\beta_c} - \frac{\beta_g}{\beta_c(\beta_g+\beta_c)})(\alpha_g + \alpha_c) \\ & + (\frac{\beta_g}{\beta_c} - \frac{\beta_g^2}{\beta_c(\beta_g+\beta_c)})q_{g1}^a + (\frac{\beta_g}{\beta_g+\beta_c} - 1)q_{c1}^a, \end{aligned} \tag{A.5}$$

$$\begin{aligned} q_{g1}^r = & \frac{\beta_c}{\beta_g+\beta_c}(q_{w1}^a - W_1) - \frac{1}{\beta_g+\beta_c}(\alpha_g + \alpha_c) \\ & - \frac{\beta_g}{\beta_g+\beta_c}q_{g1}^a + \frac{\beta_c}{\beta_g+\beta_c}q_{c1}^a. \end{aligned} \tag{A.6}$$

Given WPP's generation level w_2, the RT dispatch strategy for period 2 is

$$q_{c2}^r = \begin{cases} q_{c1}^r \pm r, \text{ if (4) is binding;} \\ \frac{\beta_g}{\beta_g+\beta_c}(q_{w2}^a - W_2) + (\frac{1}{\beta_c} - \frac{\beta_g}{\beta_c(\beta_g+\beta_c)})(\alpha_g + \alpha_c) + \\ (\frac{\beta_g}{\beta_c} - \frac{\beta_g^2}{\beta_c(\beta_g+\beta_c)})q_{g2}^a + (\frac{\beta_g}{\beta_g+\beta_c} - 1)q_{c2}^a, \\ \text{ if (4) is not binding.} \end{cases} \tag{A.7}$$

$$q_{g2}^r = \begin{cases} q_{w2}^a - W_2 - (q_{c2}^r \pm r), \\ \text{ if (4) is binding;} \\ \frac{\beta_c}{\beta_g+\beta_c}(q_{w2}^a - W_2) - \frac{1}{\beta_g+\beta_c}(\alpha_g + \alpha_c) - \\ \frac{\beta_g}{\beta_g+\beta_c} q_{g2}^a + \frac{\beta_c}{\beta_g+\beta_c} q_{c2}^a, \\ \text{ if (4) is not binding.} \end{cases} \tag{A.8}$$

I argue that a strategic WPP, which is defined as a RC, will not strategically hold back its generation capacity and generating electricity up to $min\{W_j, q_j^a\}$ MWhs. If the WPP's generation q_{wj}^r is less than $min\{W_j, q_j^a\}$ MWhs in hour j, its net benefit is $-p_j^r(q_j^a - q_j^r)$ instead of $min\{0, -p_j^r(q_j^a - W_j)\}$. Consequently, the WPP's net profit decreases. Therefore, I have the following corollary.

Corollary Appendix A.1. *The WPP's optimal strategy in the RT market is to adopt the price-taker strategy, therefore it has no ability to affect the RT price.*

Appendix B. WPP's marginal commitment costs (MCC)

Parallel with the RID curve, the WPP's MCC curve also affects the WPP's ability to manipulate the price. In contrast with the RID curve that reflects the price sensitivity to the WPP's commitment, the MCC curve reflects the WPP's marginal-cost sensitivity to its own commitment. The MCC curve associated with the RID curve determines the WPP's market-power commitment q_{wj}^{a*} and price-taker commitment ${q'_{wj}}^a$, which together determine the inverse elasticity of the WPP's RID curve. Furthermore, the WPP's MCC also determines the WPP's willingness to exercise its market power. If the MCC quickly increases as the WPP's commitment grows, the WPP has high incentive to exercise its market power for not just inflating price but also preventing high marginal commitment costs. In the rest of this section, I analyze the WPP's MCC curve in hour 2, in which the net demand is high. The conclusions can be symmetrically generalized to get the characteristics of the MCC in hour 1, in which the net demand is low.

Because of the effects of G_c' ramp rate, the WPP's MCC curve in my three-generator case is a discontinuous function. I conceptually show the WPP's MCC curves of the two hours in Fig. 1. The RID's tipping point also splits the MCC curve in the same hour. The WPP's MCC curve of hour 2 in the DA market is a piece-wise function described in the following equation.

$$mcc_2 = \begin{cases} \int_0^{q_{w2}^a} \chi(w_2) f(w_2) dw_2 + q_{w2}^a \{Prob(W_1 \geq q_{w1}^a \cup (W_1 < q_{w1}^a \cap W_2 < W_1 - \frac{\beta_g+\beta_c}{\beta_g} r))\beta_g \\ +Prob(W_1 < q_{w1}^a \cap W_2 \geq W_1 - \frac{\beta_g+\beta_c}{\beta_g} r) \frac{\beta_c}{\beta_g+\beta_c}\beta_g\}, \text{ if } q_{w2}^a < RTP_2; \\ \int_0^{q_{w2}^a} \chi'(w_2) f(w_2) dw_2 + q_{w2}^a \{Prob(W_2 < q_{w2}^a \cap W_2 < W_1 - \frac{\beta_g+\beta_c}{\beta_g} r)\beta_g \\ +Prob(W_2 \geq q_{w2}^a \cup (W_2 < q_{w2}^a \cap W_2 \geq W_1 - \frac{\beta_g+\beta_c}{\beta_g} r)) \frac{\beta_c}{\beta_g+\beta_c}\beta_g\}, \text{ if } q_{w2}^a \geq RTP_2; \end{cases} \tag{B.1}$$

Here, given w_2, χ and χ' are functions of demands and conventional GenCos' bidding curves. The WPP's MCC curve's discontinuity reselects the heterogeneity of the MCC's sensitivity to its own commitment, as in Eq. B.1. When the WPP's commitment $q_{wj}^a < RTP_j$, the WPP's MCC is more sensitive to its own commitment than in the scenario when $q_{wj}^a \geq RTP_j$.

The MCC's sensitivity is heterogenous with respect to its own commitment because of two reasons. First, the RT-price sensitivity with respect to the WPP' DA commitment is different by whether G_c's ramp constrain is binding in the RT market. Second, as shown in Fig., the probability of that G_c's ramp constrain is binding in the RT market discontinuously jumps to a significantly high level if the WPP increase its commitment q_{w2}^a from just lower than RTP_2 to just higher than RTP_2. Therefore, the WPP's MCC curve discontinuously drops to a low level at RTP_2 and has flatter slope when $q_{w2}^a > RTP_2$ because the MCC is the expected RT-price. (Because the fact the $q_{w2}^a < RTP_2$ will essentially expand the probability of the situation that G_c's ramp constrain is binding, under which situation the RT price p_r is more sensitive to q_{w2}^a, the WPP's MCC $E[p_2^r]$ is more sensitive to q_{w2}^a when $q_{w2}^a < RTP_2$ than when $q_{w2}^a \geq RTP_2$. Consequently, the MCC curve has steeper slopein the segment of $q^a_{wj} < RTP_j$ than in the segment of $q^a_{wj} \geq RTP_j$.)

By summarizing above analyse, I have the following theorem.

Theorem Appendix B.1. *If a GenCo's ramp constrain is becoming binding because a WPP reduces its DA commtiment, the WPP's MCC is a discontinuous increase function of its own commitment. The MCC is more sensitive to the WPP's DA commitment when the GenCo's ramp constrain is binding than when the constrain is not binding.*

Proof. First, the probability of the situation that G_c' ramp constrain is binding in the RT market changes with the WPP's DA commitment q^a_{w2} discontinuously at the point RTP_2. As shown in Eq.(B.1), G_c' ramp rate has much more opportunity to limit its generation in the RT market if $q^a_{w2} < RTP_2$ than in the scenario if $q^a_{wj} \geq RTP_j$. I would like to emphasize that the fact that G_c's ramp constrain is binding in the DA market does not necessarily indicate that the same constrain is binding in the RT market. For example, if the WPP's generation in the hour 1 is sufficiently small in RT market, G_c can generate more than its commitment in hour 1 such that $q^r_{w2} > q^a_{w2}$. Consequently, G_c's generation capacity in hour 2 is $q^r_{w1} + r$ in the RT market instead of $q^a_{w2} + r$ and the ramp constrain can be no binding. I in Fig. compare the probability of ramp-constrain binding given the WPP's different DA commitment levels. If $q^a_{w2} < RTP_j$, G_c's generation will not be constrained only if the WPP's generation capacities in both two hours are less than the commitment levels and $W_2 - W_1$ is sufficiently large. In contrast, if $q^a_{w2} \geq RTP_2$, G_c's generation will not be constrained once the WPP's generation capacity W_2 in hour 2 is large than its commitment or $W_2 - W_1$ is relatively large when $W_j < q^a_{wj}$. Therefore, G_c are more likely to be constrained by its own ramp rate in the RT market when $q^a_{w2} < RTP_2$ than when $q^a_{w2} \geq RTP_2$.

The second reason (that causes the WPP's heterogenous MCC sensitivities to its DA commitment) is that the RT-price sensitivity to the WPP' DA commitment depends on whether G_c's ramp constrain is binding. The RT price, which determines the WPP's MCC, is more sensitive to the WPP's DA commitment if G_c's ramp constrain is binding in the RT market than if the ramp constrain is not binding. For example, the WPP's MCC in hour 2 $E[p^r_2]$, which is the expected price that the WPP needs to pay for purchasing electricity in the RT market, is more sensitive to the WPP's DA commitment q^a_{w2} when G_c' ramp constrain is binding than when the constrain is no binding. Actually, one unit more DA commitment from the WPP will inflate the RT price by β_g when G_c's ramp constrain is binding rather than by $\frac{\beta_c}{\beta_g+\beta_c}\beta_g$ when the ramp constrain is not binding. □

According to Eq. B.1, the WPP's MCC in hour 2 is also determined by G_c's ramp rate r and the WPP's commitments in both two hours, and the extend of difference between β_g and β_c. The ramp rate r and the WPP's commitments in two hours affect mcc_2 by impacting the the probability of the situation that G_c' ramp constrain is binding in the RT market. The probability is high if r is small. q_{w1}^a can affect the probability only if $q_{w2}^a < RTP_2$. In this scenario, the smaller the q_{w1}^a, the higher the provability that G_1's ramp constrain is binding in the RT market. In contrast, q_{w2}^a can affect the probability only if $q_{w2}^a \geq RTP_2$. In this scenario, the smaller the q_{w2}^a, the lower the provability that G_1's ramp constrain is binding in the RT market. I summarize the analyses in the following theorem.

Appendix C. Proofs of Theorems

Proof of Theorem 4.3

Proof. When $q_{w2}^{a*} < RTP_2$, the WPP's market-power-profit-maximization commitment level q_{w2}^{a*} is solved from

$$p_j^a\prime(q_{w2}^{a*})q_{w2}^{a*} + p_2^a(q_{w2}^{a*}) = mcc_2.$$

Therefore, q_{w2}^{a*} can be represented by $q_{w2}^{a*}(p_2^a, p_2^a\prime, mcc_2)$. In particular, when $q_{w2}^{a*} < RTP_2$, GenCos' ramp rates affect p_2^a by determining the market price p_2^a when the WPP commit to provide zero MWhs in hour j. Therefore, the change of q_{w2}^{a*} caused by a change of r can be expressed as

$$\frac{dq_{w2}^{a*}}{dr} = \frac{dq_{w2}^{a*}}{dp_2^a}\frac{dp_2^a}{d\phi_2}\frac{d\phi_2}{dr} + \frac{dq_{wj}^{a*}}{dmcc_2}\frac{dmcc_2}{dr}|_{q_{w2}^a < RTP_2}. \tag{C.1}$$

Symmetrically, $\hat{q}_{w2}^a$ is solved from

$$p_2^a(q_{w2}^{a'}) = E[p_2^r].$$

Therefore, $\hat{q}_{w2}^a$ can be represented by $\hat{q}_{w2}^a(p_2^a, mcc_2)$ when $\hat{q}_{w2}^a > RTP_2$. Then, the change of $\hat{q}_{w2}^a$ caused by a change of r can be expressed as

$$\frac{d\hat{q}_{w2}^a}{dr} = \frac{d\hat{q}_{w2}^a}{dmcc_2}\frac{dmcc_2}{dr}|_{q_{w2}^a < RTP_j}. \tag{C.2}$$

Similarly, the change of RTP_2 caused by a change of r can be expressed as

$$\frac{dRTP_2}{dr} = \frac{dRTP_2}{d\phi_2}\frac{d\phi_2}{dr}. \tag{C.3}$$

Then, if $\frac{d(RPT_j - q_{wj}^{a*})}{dr}$ is greater than $\frac{d(\hat{q}_{w2}^{a} - RTP_j)}{dr}$ when G_c's ramp rate decreases by dr, the ramp-rate decrease enlarges the vale of η as well as enhances the WPP's ATMP. Because r's change only affect RIP_2 when $q_{w2}^{a} < RTP_2$, the change of r impacts $q_{wj}^{a*})$ by increasing both RIP_2 and mcc_2 curve. The increases of RIP_2 and mcc_2 curve have opposite effects on $q_{wj}^{a*})$. In contrast, the change of r impacts $\hat{q}_{w2}^{a}$'s only by steeping mcc_2. Furthermore, the piece of mcc_2 in between $q_{w2}^{a} \in [0RTP_2]$ is steeper than the piece of $q_{w2}^{a} > RTP_2$. Therefore, $\frac{d(RPT_j - q_{wj}^{a*})}{dr}$ is always greater than $\frac{d(\hat{q}_{w2}^{a} - RTP_j)}{dr}$. Consequently, the ramp-rate decrease enlarges the vale of η as well as enhances the WPP's ATMP.

Following similar processes, I can demonstrate that L_1's decrease and q_{w2}^{a}'s increase enlarge the vale of η as well as enhances the WPP's ATMP. □