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Analyzing Firm Behaviour in Restructured Electricity Markets: Empirical Challenges with a Residual Demand Analysis

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by

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Abstract

Using data from Alberta's wholesale electricity market, we demonstrate the empirical challenges that can arise when employing empirical methodologies to characterize a firm's unilateral profit-maximizing offer curve. We illustrate that such residual demand analyses can result in non-monotonic, downward sloping, optimal best-response offer curves violating restrictions imposed on bidding behaviour. We show that this arises because of the highly non-linear nature of residual demand functions firms can face in practice. We find that firms could have achieved the vast majority of expected profits by employing an offer curve that represents a monotonically smoothed version of the often non-monotonic optimal offer curves. Our findings shine light onto empirical challenges associated with commonly employed equilibrium models to analyze firm behaviour in restructured electricity markets. Further, our analysis illustrates that the failure to account for these empirical challenges may lead researchers to incorrect conclusions regarding observed firm behaviour. These findings stress the importance of accounting for regulatory and practical constraints firms face when modeling bidding behaviour in these multi-unit, uniform-priced, procurement auctions.

Keywords: Electricity, Market Power, Regulation
JEL Codes: D43, L40, L51, L94, Q48

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1 Introduction

The measurement of market power and evaluation of firm behaviour is an important issue in concentrated wholesale electricity markets where firms interact repeatedly. Market power has been shown to lead to substantial market inefficiencies and rent transfers from consumers to producers (Borenstein et al., 2002; Wolak, 2003; Brown and Olmstead, 2017).[1] Further, evaluations of firm behaviour have raised concerns of coordinated conduct (Sweeting, 2007; Brown and Eckert, 2019). These concerns have led to various market reforms and the implementation of policies to regulate the degree to which firms are able to bid above marginal costs (FERC, 2014; AUC, 2017).

Numerous approaches have been established to evaluate firm behaviour that are utilized by researchers and regulators worldwide. These techniques are essential to evaluate the performance of electricity markets and allows regulators to investigate whether firms can be viewed as acting independently to unilaterally maximize profits or whether the firm behaviour is indicative of some form of coordination. In this paper, we illustrate empirical issues that can arise in a real-world setting with the implementation of recent methods established to analyze these questions.

Unlike other industries, the use of concentration measures to evaluate industry structure such as the Herfindahl-Hirschmann Index has been shown to be a poor measure of market power in electricity markets due to their inability to account for transmission constraints, elasticity of demand, and the intertemporal variation in firms' abilities to exercise market power (Borenstein et al., 1999). This led to the proliferation of a literature that compares observed firm behaviour to a perfectly competitive benchmark (e.g., Wolfram (1999), Borenstein et al. (2002), Brown and Olmstead (2017)). This literature often finds that firms exercise substantial market power elevating wholesale prices and resulting in large productive inefficiencies.

There is a growing empirical literature that evaluates whether firms are bidding in a manner that is consistent with unilateral expected profit maximization (Wolak, 2000, 2003, 2007; Hortaçsu and Puller, 2008; McRae and Wolak, 2014; Mercadal, 2018).[2] While the details and methods differ across each study, these analyses utilize models that characterize a firm's unilateral expected profit maximizing (best-response) supply function facing a stochastic residual demand function that represents market demand net of its rivals' supply functions.[3] Wolak (2000, 2003) and Hortaçsu and Puller (2008) discuss conditions under which the expected profit maximizing supply function can be characterized by finding the optimal price-quantity pair that maximizes a firm's *ex-post* profit for any potential realization of residual demand.

Most relevant for our analysis, Hortaçsu and Puller (2008) utilize this methodology to map out each firm's optimal offer curve and compare it to observed behaviour in Texas's wholesale electricity

[1]For example, in Borenstein et al.'s (2002) analysis of the California electricity crisis, the authors find that oligopoly rents increased from \$425 million to \$4.4 billion between 1998 and 2000 due to market power execution.

[2]This literature is motivated by the theoretical foundations established by Wilson's (1979) share auction model and Klemperer and Meyer's (1989) Supply Function Equilibrium.

[3]Using a firm's residual demand function to assess its market power was initiated in the structural analysis of markets with differentiated products; see for example Baker and Breshahan (1988).

market. The authors find that large firms bid in a manner that is consistent with unilateral expected profit maximization, while smaller firms deviate from this benchmark.[4] Mercadal (2018) extends this analysis to consider forward financial markets and transmission constraints.

In this article, we utilize data from Alberta's wholesale electricity market for a time period during which generating firms were alleged to have engaged in coordinated behaviour.[5] We focus our analysis on three firms that make up approximately 40% of the market. We demonstrate the challenges that can arise when employing existing methodologies to characterize a firm's unilateral expected profit maximizing offer curve. We show that a firm's residual demand can be highly non-linear with large shelves and vertical portions; similar residual demand curve characteristics appear in Australia (Wolak, 2007), Spain (Reguant, 2014), Italy (Bigerna et al., 2016) and New York (Benatia, 2018). We find that these features can result in profit functions that are non-concave with multiple local optima. We demonstrate that both the multiplicity of local optima and local convexity of residual demand functions can result in backward bending (downward sloping) best-response offer curves violating restrictions in practice that supply functions must be monotonically increasing.[6] We characterize conditions under which these empirical problems will arise.

We present evidence suggesting that two of the three large strategic firms in our sample bid in a manner that is inconsistent with the supply function that passes through the *ex-post* profit maximizing price-quantity pairs, whereas the third firm bids closely to this benchmark. However, because the optimal offer curve is often non-monotonic, these results could be driven in part by the fact that firms are unable to bid in a manner consistent with this benchmark. To investigate this possibility, we construct alternative monotonic offer curves that represent a monotonic smoothing of the optimal offer curves. We illustrate that the firms in our sample could have recovered the vast majority of expected profits by utilizing the monotonically smoothed optimal offer curves. However, for two of the three firms, we illustrate that their bidding behaviour often deviated from even the monotonically smoothed optimal offer curves. These findings contrast with evidence from other jurisdictions that fail to rejected expected profit-maximization by large firms such as Australia (Wolak, 2007) and Texas (Hortaçsu and Puller, 2008).

These findings emphasize that an offer curve that maximizes a firm's expected profit may not pass through the *ex-post* profit-maximizing price-quantity pairs in every period due to monotonicity restrictions imposed in practice. As a result, empirical approaches that impose this *ex-post* assumption may lead researchers to conclude that firms are not behaving in a manner consistent with unilateral expected profit maximization. In particular, it may appear as though firms could unilaterally increase profit by increasing output, suggesting they may be engaged in coordi-

[4]Hortaçsu et al. (2019) find that deviations from unilateral expected profit maximization by smaller firms reflects a lack of overall strategic sophistication and bounded rationality.

[5]For details see MSA (2013b), Brown et al. (2018), and Brown and Eckert (2019).

[6]Holmberg and Willems (2015) demonstrate that firms may have an incentive to submit downward sloping supply functions in wholesale electricity markets. However, unlike our analysis, the primary motivation for their result is the strategic incentives introduced by the trading of forward call options prior to wholesale market competition.

nated behaviour to withhold output to elevate prices. However, firms may in fact be unilaterally maximizing their expected profit subject to the constraint that their offer curves have to be monotonically increasing. While this does not seem to be the explanation for why firms deviated from this benchmark in our setting, this can lead to incorrect conclusions in other cases.

Wolak (2007, 2010, 2015) discusses the potential for the *ex-post* optimal offer curve to be unobtainable in practice because of bidding restrictions (such as monotonicity). For example, Wolak (2015) notes through a graphical discussion that the *ex-post* profit maximizing offers may trace out a downward sloping offer curve. Wolak (2007, 2010) present a sophisticated econometric methodology to estimate the expected unilateral profit-maximizing offer curve subject to bidding restrictions imposed on firms' offer curves. Notably, this literature does not consider the extent to which *ex-post* optimal offer curves violate monotonicity constraints, or the particular reasons and circumstances under which this likely to occur; these questions motivate the current paper.[7,8] In addition, our paper assesses the extent to which a simple rule-of-thumb smoothing of the *ex-post* optimal offer curve can capture potential expected profits. We find that employing the outer envelope of the *ex-post* optimal offers achieves the vast majority of available firm profits.

Finally, there is a broader literature that analyzes the impacts of restrictions imposed on bidding behaviour in multi-unit divisible goods auctions. Kastl (2011, 2012) and Holmberg et al. (2013) analyze the impact of restricting the number of steps in an agent's bid function. Further, Kastl (2012) and Woodward (2019) account for monotonic restrictions imposed on bidding in a theoretical framework. These studies demonstrate that these practical bidding restrictions can induces bidders to adjust the their bid functions impacting equilibrium outcomes. Our analysis contributes to this literature by provide additional empirical evidence on settings under which bidding restrictions and conditions on residual demand can induce agents to adjust their offer behaviour in multi-unit auctions.

The paper is organized as follows. Section 2 presents the theoretical foundations. Section 3 provides an illustrative example of the empirical challenges that arise in our setting. Section 4 presents our main empirical application, data, methodology, and results. Section 5 concludes.

2 Theoretical Foundations

We describe models that are employed to construct a firm's unilateral expected profit maximizing offer curve given the offers submitted by its rivals. These models demonstrate that under certain conditions, the unilateral expected profit-maximizing offer curve reduces to finding the price-quantity pairs that maximize a firm's *ex-post* profit for all possible residual demand curve realizations (Wolak, 2000, 2003; Hortaçsu and Puller, 2008; McRae and Wolak, 2014).[9]

[7] The potential for profit functions with multiple local optima has been recognized in the engineering literature devising bidding mechanisms for firms; see Baillo et al. (2004) and Xu et al. (2011).

[8] The restriction that firms must bid monotonic offer curves in electricity markets is accounted for in Reguant (2014) who uses offer data and assumes expected profit maximization to estimate firms' cost function parameters.

[9] Several of these contributions are motivated by the seminal contribution of Klemperer and Meyer's (1989) Supply Function Equilibrium (SFE) model which allows firms to submit supply functions facing uncertainty in aggregate

First, consider the modeling framework utilized in Wolak (2000, 2003) and McRae and Wolak (2014). Define $RD_{it}(p, \epsilon_{it})$ to be the residual demand faced by a firm i in period t, where p represents market price and ϵ_{it} is a stochastic component. Residual demand represents market demand less the aggregate supply curves submitted by all other firms in the market. Define $C_{it}(q)$ to be firm i's total cost of producing q units of output. We assume that firm i has also signed a certain number of forward contracts in advance of the wholesale market at a price p^f_{it} and quantity q^f_{it}. These contracts are taken as given when firms make their wholesale market bidding decisions.[10] For any given ϵ_{it} realization, this results in the following variable profit function:

$$\pi_{it}(p, \epsilon_{it}) \;=\; p\left[RD_{it}(p, \epsilon_{it}) - q^f_{it}\right] - C_{it}(RD_{it}(p, \epsilon_i)) + p^f_{it}q^f_{it} \tag{1}$$

where $RD_{it}(p, \epsilon_{it}) - q^f_{it}$ represents the quantity produced by firm i beyond its forward contracted quantity. If this term is negative, firm i is a net purchaser on the wholesale market.

Following Wolak (2000, 2003), under certain conditions, firm i's expected profit-maximizing supply curve is the function that passes through all *ex-post* profit maximizing price-quantity pairs for all possible residual demand realizations. Consequently, for any residual demand realization, the following first-order condition holds for firm i:

$$RD_{it}(\cdot) - q^f_{it} + \left[p - C'_{it}(RD_{it}(\cdot))\right] RD'_{it}(\cdot) \;=\; 0 \tag{2}$$

where $RD'_{it}(\cdot)$ and $C'_{it}(\cdot)$ represents the first derivative of the residual demand and total cost functions, respectively.

Recognizing that firm i's supply function $S_{it}(p)$ equals the residual demand at the resulting market clearing price for any realized residual demand function in this setting (i.e., $S_{it}(p) = RD_{it}(p, \epsilon_{it})$), (2) can be rewritten as:

$$p - C'_{it}(S_{it}(p)) \;=\; \frac{S_{it}(p) - q^f_{it}}{-RD'_{it}(\cdot)} \tag{3}$$

Second, Hortaçsu and Puller (2008) extend Wilson's (1979) share auction model to characterize optimal offer behaviour where firms submit supply functions facing stochastic residual demand and uncertainty in their rivals' forward contract positions. The authors demonstrate that if bids are additively separable in price and firms' contract positions and profit functions are concave, the optimality condition is analogous to that specified in (3). Under these conditions, similar to Wolak (2000, 2003), the optimal supply function reflects the *ex-post* profit-maximizing price-quantity pair for any residual demand realization.

demand. The SFE model has been extended and utilized in a large empirical literature that analyzes firm behaviour in electricity markets; see Holmberg and Newbery (2010) for a detailed review. The authors focus on characterizing an equilibrium outcome for each firms' supply functions and impose sufficient restrictions on demand, costs, and stochastic demand shocks so that firms submit monotonically increasing supply curves that trace out the *ex-post* profit maximizing price-quantity pair for any realization of the aggregate demand uncertainty.

[10]For additional details on forward contracting in electricity markets, see Wolak (2007).

Figure 1: Illustration of Deriving the Optimal Supply Function

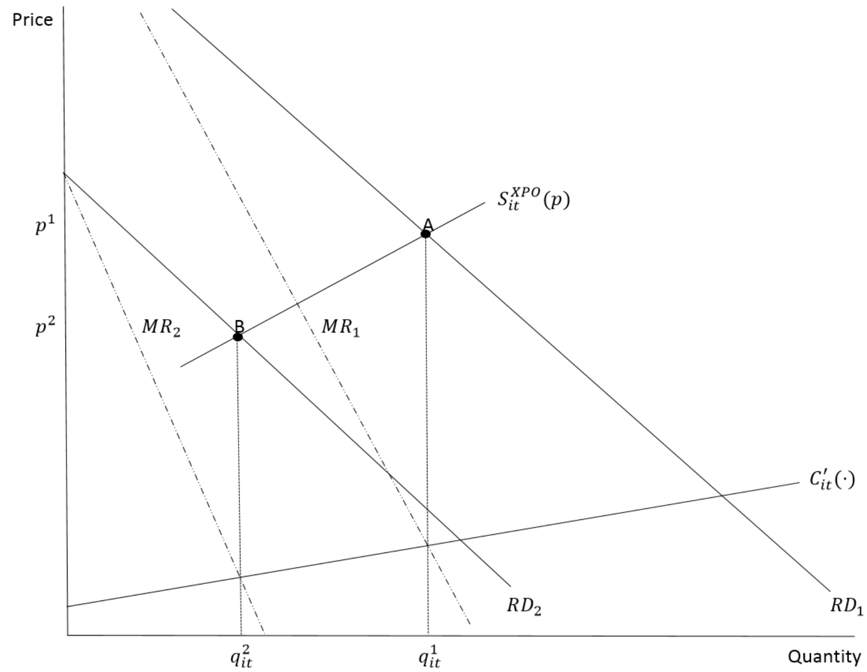


Figure 1 illustrates the construction of the optimal supply function for two potential residual demand curve realizations (RD_1 and RD_2). For each residual demand curve, the *ex-post* profit-maximizing quantity arises at the intersection of the marginal revenue and marginal cost curves (i.e., $MR_j = C'_{it}(\cdot)$ for $j = 1, 2$). The optimal price reflects the point on the residual demand curve at each of the optimal quantities. Under certain conditions, the optimal supply function ($S_{it}^{XPO}(p)$) crosses through points A and B as it passes through the *ex-post* profit-maximizing price-quantity pairs for any residual demand realization. It is important to notice that at points A and B, the optimality condition (3) is satisfied. As discussed in more detail below, this figure demonstrates the empirical strategy that is utilized to trace out a firm's optimal supply function.

We characterize necessary and sufficient conditions that ensure the model presented in (1) - (3) is sufficiently well-behaved such that there is a unique optimal price-quantity pair for any ϵ_{it} realization and the resulting optimal offer curve is non-decreasing. Using (2), the second-order derivative of firm i's profit function can be written as:

$$2\,RD'_{it}(\cdot) + [\,p - C'_{it}(RD_{it}(\cdot))\,]\,RD''_{it}(\cdot) - C''_{it}(\cdot)\,[\,RD'_{it}(\cdot)\,]^2 \tag{4}$$

where $RD''_{it}(\cdot)$ and $C''_{it}(\cdot)$ represents the second derivative of the residual demand and total cost functions, respectively. If the expression in (4) is strictly negative, then firm i's profit function is strictly concave. In this setting, there exists a unique price-quantity pair for each ϵ_{it} realization. A sufficient condition to ensure that (4) is negative arises if price weakly exceeds marginal cost ($p - C'_{it}(\cdot) \geq 0$), residual demand is weakly concave ($RD'_{it}(\cdot) < 0$ and $RD''_{it}(\cdot) \leq 0$), and total cost is weakly convex ($C'_{it}(\cdot) \geq 0$ and $C''_{it}(\cdot) \geq 0$).

Suppose the residual demand function is downward sloping and cost is weakly convex (i.e., $RD'_{it}(\cdot) < 0$ and $C''_{it}(\cdot) \geq 0$). The slope of the *ex-post* optimal supply function $S_{it}(p)$ implied by (3) is non-decreasing when:[11]

$$S'_{it}(p) \;\geq\; 0 \quad \Leftrightarrow \quad \text{Monotonic Supply Cond.} \equiv RD'_{it}(\cdot) + [\,p - C'_{it}(\cdot)\,]RD''_{it}(\cdot) \;\leq\; 0. \tag{5}$$

(5) implies that the *ex-post* optimal supply function is non-decreasing as long as the second term in the Monotonic Supply Cond. is not sufficiently positive. It is important to notice that both the strict concavity of the profit function and the monotonicity of the ex-post optimal supply function depend critically on the sign and magnitude of $RD''_{it}(\cdot)$. As shown by (4) and (5), if residual demand is sufficiently convex at certain price levels (i.e., $RD''_{it}(\cdot) > 0$), then firm i's profit function can be locally convex and the *ex-post* optimal supply function can be downward sloping.

We can demonstrate that the non-decreasing supply condition is more stringent than strict concavity of the profit function. Using (5), (4) can be rewritten as:

$$RD'_{it}(\cdot) + \text{Monotonic Supply Cond.} - C''_{it}(\cdot)\,[\,RD'_{it}(\cdot)\,]^2. \tag{6}$$

(6) implies that the strict concavity of firm i's profit function can be satisfied while the Monotonic Supply Cond. fails to hold (i.e., (6) can be negative even though Monotonic Supply Cond. $>$ 0). This implies that the *ex-post* optimal supply function can be non-monotonic even in the absence of multiple local equilibria. Consequently, the monotonic supply function restriction imposes a more stringent restriction on the shape of residual demand.

It is useful to note that the implications of non-concave profit and demand functions in our setting are related to results from the literature on taxation and cost pass-through in the presence of market power. The possibility that a monopolist's profit function may exhibit multiple optima, so that marginal policy changes such as tax adjustments may have discretely large effects, is discussed for example in Guesnerie and Laffont (1978). In addition, it has been shown that the curvature of market demand affects the pass-through of tax increases (e.g., see Weyl and Fabinger, 2013); under a sufficiently convex demand curve, pass-through can be greater than 100%.

In the remainder of the paper, we illustrate that the conditions necessary to ensure that there is a unique price-quantity pair for each realization of residual demand and the assumptions imposed on the curvature of the residual demand function in (5) can fail to hold empirically. We demonstrate that these issues can result in non-monotonic optimal offer curves. This can have important consequences on the empirical methodology utilized to map out the *ex-post* optimal offer curves using the best-response pricing methodology outlined above.

[11] See the Appendix for a detailed derivation.

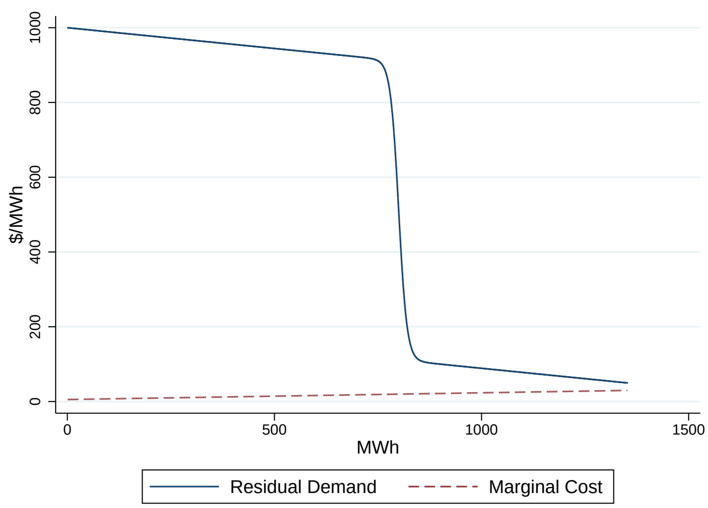
3 Numerical Example

In this section, we present an illustrative example to demonstrate the empirical challenges that can arise when identifying a firm's best-response offer curve in the presence of a non-concave residual demand curve. Throughout this example, suppose that the firm has forward contracted 700 MWhs in advance of the wholesale market. Further, suppose that a large firm with a marginal cost curve given by $MC(q) = 5.36 + 0.018\,q$ faces an expected residual demand curve of the form:

$$RD(q) = 1000 - \frac{800}{1 + exp(-0.1 * (q - 800))} - \frac{q}{9} \tag{7}$$

The expected residual demand and marginal cost curves are illustrated in Figure 2.[12] Our residual demand curve captures key features observed in some wholesale electricity markets: a flat "shelf" at high prices, a steep vertical segment, and a second flat segment at low prices. As will be discussed below, this form of residual demand curve shape arises systematically in our data.

Figure 2: Expected Residual Demand and Marginal Cost Curves - Numerical Example



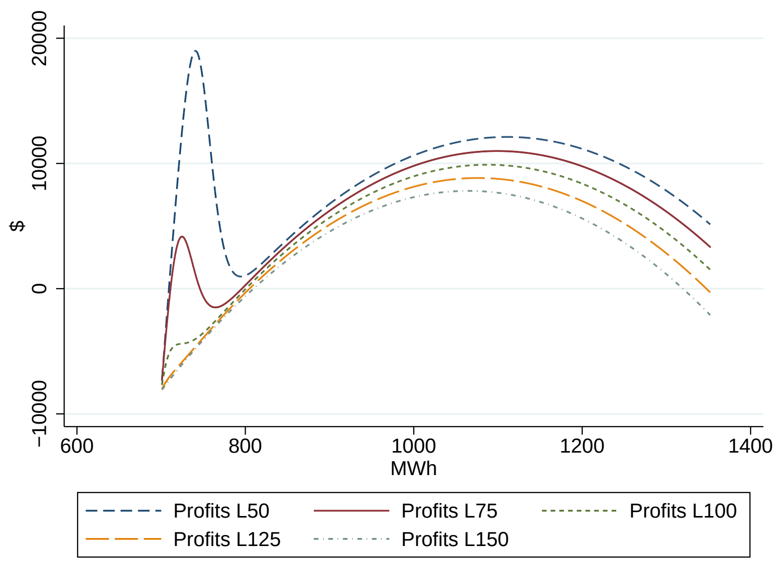
Following the literature in Section 2, one might attempt to characterize the unilateral expected profit-maximizing offer curve by finding the optimal price-quantity pairs that maximize the firm's *ex-post* profit for all possible residual demand curve realizations. For illustrative purposes, suppose the uncertainty associated with a firm's residual demand curve results in parallel shifts of the expected residual demand function given in equation (2) (recall Figure 1). It can be shown that this residual demand curve results in a non-concave profit function with multiple local maxima.

Using (4) and noting that our marginal cost curve is linear, the non-concavity of the profit function occurs where residual demand is sufficiently convex. To illustrate, Figure 3 presents the

[12]This example is modeled after a single hour in Alberta's wholesale electricity market: March 6, 2013 Hour Ending (HE) 21 (i.e., 8:00 - 9:00 PM), and the firm Capital Power. Further details on the Alberta market and residual demand curves faced by this firm are given in Section 4.

profit functions associated with shifting the residual demand curve given in (2) leftward in a parallel fashion by 50, 75, 100, 125, and 150 MWhs.[13] Notice, there are two local optima. For the left 50 residual demand curve (L50), the global optimal outcome arises at the lower quantity (higher price) outcome. As residual demand shifts further to the left, the higher quantity (lower price) optimum begins to dominate, until eventually there is only one global maximum at the higher quantity. Alternatively, it can be shown that as demand shifts to the right, the global optimum is systematically represented by the low quantity (high priced) outcome. Intuitively, as residual demand shifts further to the right, it is more attractive to restrict output and increase price.

Figure 3: Firm Profit with Leftward Shifted Residual Demands

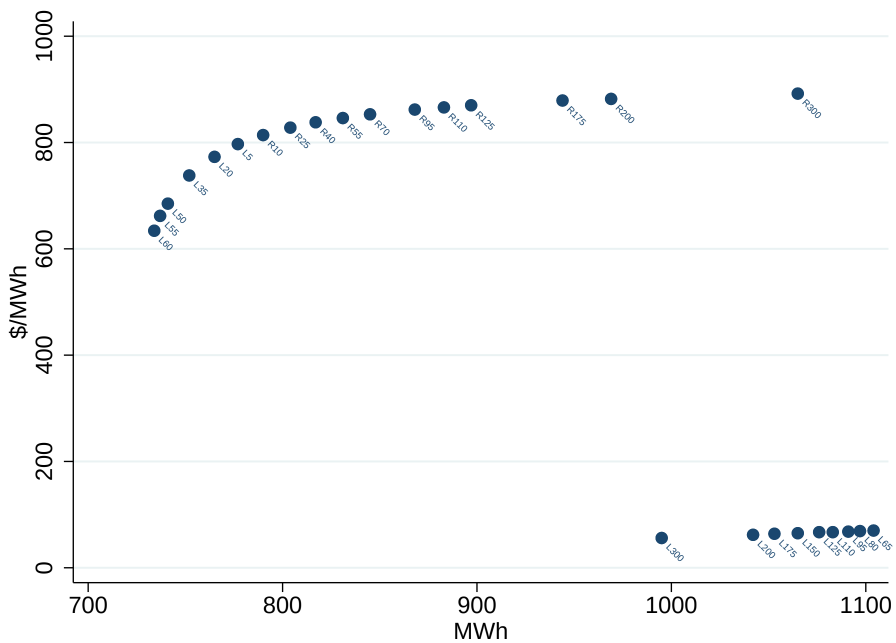


We use this approach to trace out the price-quantity pairs that maximize a firm's *ex-post* profit for each realized residual demand curve, focusing on the global optimum. Figure 4 presents the (globally) optimal non-monotonic offer curve that arises from parallel shifts of the residual demand function. In this numerical example, the non-monotonicity arises due to the non-concavity of the residual demand function which results in multiple local optima (recall the discussion in Section 2). More specifically, as shown in Figure 4, for the right-most residual demand curve, the optimal price-quantity pair reflects the low quantity (high priced) local optima illustrated in Figure 3. As residual demand shifts towards the left, the optimal price-quantity pair moves downward to the left at lower prices and quantities, but the global optimum continues to reflect the lower quantity local optima. Eventually, as shown in Figure 3, for a sufficiently leftward shifted residual demand curve there is a discontinuous "jump" in the identity of the global optima to the local optima with a higher quantity (lower price). Further leftward shifts in the residual demand curve remain at

[13]Using (1), variable profit reflects $\widetilde{\pi}_{it}(\cdot) = p\left[RD_{it}(\cdot) - q^f_{it}\right] - C_{it}(\cdot)$ which ignores (unobservable) revenues from forward commitments $(p^f_{it}q^f_{it})$ and fixed costs. This has no impact on our results as these factors are invariant to firm i's output.

this local optima, but the optimal price-quantity levels decrease.

Figure 4: *Ex-post* (Globally) Optimal Offer Curve



It is important to note that both the left-most and right-most local optima illustrated in Figure 3 satisfy the first-order condition defined in (2). Further, if we were to ignore the multiplicity issue and focus solely on tracing out either local optima, rather than identifying the global optimal best-response price-quantity pair, we could trace out a monotonically increasing offer curve (e.g., see Figure 4). This may lead researchers to incorrectly identify the *ex-post* optimal offer curve.

4 Empirical Application

The numerical example in Section 3 highlights empirical challenges that can arise when estimating a firm's best-response bidding strategy. In this section, we utilize data from Alberta's wholesale electricity market to demonstrate that these empirical challenges can arise in practice. We will show that non-monotonic *ex-post* optimal supply curve issues can also arise absent the presence of multiple local equilibria. Further, we find that a firm could have achieved a large portion of the expected profits that would arise under the non-monotonic *ex-post* optimal offer curves via a monotonic smoothing of the optimal offer curve.

4.1 Alberta's Wholesale Electricity Market

Alberta's wholesale electricity market operates as a single hourly uniform-price procurement auction. There is no day-ahead market. For each hour, firms may submit up to seven price-quantity pairs for each of their generating units. Prices must be non-negative and less than \$999.99/MWh.[14]

[14]Importantly, firms are only able to submit "simple" bids that consist of an array of price-quantity pairs. This is in contrast to other jurisdictions where firms are also permitted to submit fixed components that aim to recover

All available capacity from a generating unit must be offered. The offer curves submitted by a firm are required to be non-decreasing.

The Alberta Electric System Operator (AESO), who coordinates the market, orders the offer blocks in increasing order of price. The offer blocks are called upon (dispatched) to supply electricity until demand is met. The system marginal price (SMP) is the offer price of the highest-priced block dispatched at any moment in time. The pool price for an hour is the time weighted average of the SMPs; this is paid to all units that provided electricity throughout the hour.

Alberta's wholesale market is "energy-only" meaning that firms are only compensated for energy produced, and do not receive any additional capacity payments.[15] To allow recovery of fixed costs of generation capacity investment, Alberta explicitly permits firms to exercise unilateral market power and as a result there is no bid mitigation (MSA, 2011). This makes Alberta an ideal environment to investigate unilateral market power execution.

In 2013, Alberta's wholesale market was moderately concentrated, with five firms (ATCO, Capital Power (CP), ENMAX, TransAlta (TA), and TransCanada (TC)) having control of over 64% of Alberta's generation capacity (MSA, 2013a). Alberta's market is dominated by fossil-fuel generation with coal (43%) and natural gas (40%) making up the vast majority of installed capacity in 2013 (AUC, 2013).[16] Our empirical analysis focuses on the behaviour of three firms: ATCO, Capital Power, and TransCanada. During our sample, these firms are merchant generation companies who only participate in the wholesale market.[17] Further, as noted in Brown and Eckert (2019), these firms are believed to be large strategic actors during our sample period.

4.2 Data

Our analysis makes use of publicly available data for the year 2013 from the AESO on hourly price-quantity offers by firm and generating asset, along with data on import supply and capacity, wind output, market demand, and generation asset characteristics. In addition, in order to compute short-run marginal cost, we utilize natural gas price data from Alberta's Natural Gas Exchange and coal prices for Wyoming's Powder River Basin from the Energy Information Administration.

For illustrative and tractability purposes, we focus our attention on March 2013 peak demand hours (11:00 AM - 10:00 PM). These hours reflect high demand hours where strategic behaviour is most likely (Brown and Olmstead, 2017). Further, we focus our attention on March because this month had an irregular number of high priced periods (MSA, 2013c). This suits our purposes well

cost components such as start-up costs. Reguant (2014) demonstrates that these "complex" bidding structures can complicate an analysis of bidding behaviour considerably.

[15] Numerous jurisdictions in North America provide capacity payments in addition to revenues earned from wholesale markets. These payments aim to motivate investment in generation capacity in order to alleviate concerns of under-investment in "energy-only" markets. For a detailed discussion, see Cramton et al. (2013).

[16] For additional details on Alberta's electricity market, see Brown and Olmstead (2017).

[17] Of the other two firms, ENMAX and TransAlta, ENMAX is vertically integrated into retail, and TransAlta has an inflexible portfolio that includes coal and hydroelectric units that are subject to long-term fixed-priced contracts. As a result, these two firms' incentives are not approximated well by the theoretical model in Section 2.

as we aim to investigate the performance of models utilized in the literature to evaluate if firms are behaving in a manner that is consistent with unilateral expected profit maximization.

Table 1 presents summary statistics for several key firm and market-level variables. The hours under consideration have high average market prices and demands. Calculating a firm's realized profits is complicated by the fact that we do not have data on forward market prices (i.e., p^f_{it} in (1)). Consistent with the literature, suppose for illustrative purposes there is no arbitrage opportunities between the forward and spot (wholesale) markets such that forward prices equal spot market prices (e.g., Allaz and Vila (1993)). In this setting, average hourly spot market profits for Capital Power, TransCanada, and ATCO are \$132,135, \$175,926, and \$93,864, respectively.[18] These average variable profits, which do not incorporate dynamic start-up or fixed costs, will be used as illustrative benchmarks below.

Table 1: Summary Statistics

	Unit	Mean	Std Dev	Min	Median	Max
Market Price	\$/MWh	151.84	221.14	10.80	44.00	910.47
Market Demand	MWh	8,558.83	321.09	7,699.56	8,601.58	9,135.15
Total Output - CP	MWh	951.23	152.41	625.00	930.00	1,353.00
Total Output - TC	MWh	1,242.40	159.58	954.00	1,235.00	1,670.00
Total Output - ATCO	MWh	656.18	109.14	437.00	659.00	971.00
Total Cost - CP	\$	12,296.23	2,729.38	7,794.32	11,801.04	20,064.11
Total Cost - TC	\$	12,715.01	2,930.66	7,542.80	12,078.67	19,642.11
Total Cost - ATCO	\$	5,767.19	3,831.46	0.00	5,969.05	17,091.25

4.3 Methodology

We employ an empirical methodology similar to the one utilized by Hortaçsu and Puller (2008) to map out each firm's *ex-post* unilateral best-reply offer curve. We estimate a firm's expected residual demand function which equals expected market demand minus its rivals' offer curves. Because firms face uncertainty in the residual demand function, we consider uncertainty that results in parallel shifts in the residual demand function. In particular, we consider parallel shifts of ± 400 MWhs in increments of 25 MWh from the expected residual demand function.[19] For each parallel shift in residual demand, we compute the price-quantity pair that maximizes a firms' *ex-post* profit according to the condition specified in (3). This traces out a firm's *ex-post* optimal bid function over the region of possible residual demand curve realizations (recall Figure 1).

Observed residual demand functions are non-increasing step-functions. Similar to Wolak (2003) and Hortaçsu and Puller (2008), we employ a local-linear kernel smoothing approach on the observed residual demand function in order to compute $RD'_{it}(\cdot)$ necessary to estimate a firm's

[18] More specifically, using (1) and assuming that p^f_{it} equal spot prices, hourly variable profits at observe prices ($\widehat{p}$) and realized residual demand ($\widehat{\epsilon}_{it}$) equal $\pi_{it}(\widehat{p}, \widehat{\epsilon}_{it}) = \widehat{p}\, RD_{it}(\widehat{p}, \widehat{\epsilon}_{it}) - C_{it}(RD_{it}(\widehat{p}, \widehat{\epsilon}_{it}))$.

[19] Appendix B provides a detailed discussion of how we estimate a firm's expected residual demand function.

marginal revenue function and solve (3).[20] This approach also allows us to compute the second derivative of the residual demand function in order to evaluate conditions (4) and (5).

We do not have detailed data on firm's forward contract positions (q_{it}^f) which are required to solve (3). We employ the approach utilized by Hortaçsu and Puller (2008) where q_{it}^f is estimated as the quantity at which the observed offer curve intersects the marginal cost curve from below. This approach is driven by a firm's incentive to bid at or below its marginal cost of production when it is a net seller in the wholesale market (i.e., when it has forward contracted in advance of the wholesale market for quantities in excess of its actual production).

To compute each firm's marginal cost function, we estimate the marginal cost of each asset in a firm's portfolio. Marginal cost reflects the summation of fuel, operating and maintenance, and environmental compliance costs. For natural gas and coal units, we utilize data on natural gas and coal prices and asset characteristics (i.e., heat-rates) to compute marginal costs of coal and gas assets.[21] Wind assets are assumed to have a marginal cost of \$0/MWh. The firms under consideration also operate several cogeneration units which generate electricity as a by-product of an on-site industrial process (e.g., oil-sands facilities). The electricity that is not consumed on-site is sold to the wholesale market and systematically bid at a price of \$0/MWh. We assume these assets have a marginal cost of \$0/MWh.[22]

As will be shown below, the *ex-post* optimal offer curve is often non-monotonic and observed offer strategies systematically yield expected profits far below the unilateral expected profit maximizing level. In order to evaluate if the monotonicity restriction on firms' offer curves is the main driver of this divergence, we construct a counterfactual offer curve that reflects the upper envelope of the *ex-post* optimal supply curve.[23] This reflects a smoothed monotonic version of the *ex-post* optimal supply curve. While this smoothing approach is somewhat arbitrary, as we will show below, this monotonic smoothing approach is able to achieve the vast majority of expected profits that arise under the often non-monotonic *ex-post* optimal offer curve.

Throughout our analysis, we compute a firms' expected variable profit that could be obtained from a particular offer strategy. We ignore revenues from forward contracts ($p_{it}^f\, q_{it}^f$) and fixed costs which are unobservable and invariant to the offer strategy and residual demand realization. Recall, for each hour and firm, we undertake 33 simulations of potential residual demand realizations which reflect ± 400 MWhs parallel shifts in increments of 25 MWh around the estimated level of

[20]We utilize a conservatively large bandwidth of 50 MWhs in our local-linear kernel smoothing. In Appendix C, we reduce the bandwidth to 30 MWhs and discuss why reducing the bandwidth magnifies the incidence of the non-monotonicity of the optimal offer curve.

[21]Our analysis does not consider non-convex dynamic costs related to starting up generation assets. As discussed in Section 5, this is a valuable direction for future research.

[22]For a detailed discussion of computing marginal cost in our sample, see Brown and Eckert (2019).

[23]That is, for each quantity, the corresponding price on the offer curve is the maximum of the globally optimal prices associated with weakly lower quantities. More formally, for hour t denote the global optima from the 33 iterations by $\{(q_{1t}^*, p_{1t}^*), (q_{2t}^*, p_{2t}^*), (q_{3t}^*, p_{3t}^*), ..., (q_{33t}^*, p_{33t}^*)\}$, which have been sorted in increasing order of quantities (q_{it}^*). For each $q_t \geq q_{1t}^*$, define the firm's smoothed best response to equal the maximum p_{it}^*, for $q_{it}^* \leq q_t$. For $q_t < q_{1t}^*$, the smoothed best response price is set equal to marginal cost.

expected residual demand. This aims to capture the uncertainty faced by each firm and accurately capture a firm's expected variable profits. Based on our empirical estimation of uncertainty in market demand (see Appendix B), we find that this uncertainty is approximated well by a normal distribution with mean 0 and standard deviation of approximately 200. Consequently, we compute probability weights of each potential residual demand realization using this distribution. These probability weights are applied to the variable profit levels arising from each simulation to properly account for the fact that larger changes in residual demand are less likely to arise.

4.4 Results

To illustrate our methodological approach, Figure 5 presents the step-wise and smoothed expected residual demand curves, marginal cost, observed offer curve, and *ex-post* profit-maximizing offer curve for Capital Power for the hour of HE 21 (8:00 - 9:00 PM) on March 6, 2013, the hour and firm that were the basis for the example in Section 3.[24] The smoothed residual demand curve captures the overall shape of the step-wise expected residual demand curve well. While the best-response supply curve differs somewhat from our example in Section 3, the same basic features, including non-montonicity, are observed.[25] For low residual demand realizations associated with large leftward shifts (e.g., Left 350 denoted by L350), profits are maximized by Capital Power selecting an outcome with large quantities and low prices. For less extreme leftward shifts, the optimal offer curve involves higher prices but lower output. Finally, as residual demand shifts to the right, the offer curve is monotonically increasing consistent with that illustrated in Figure 4.

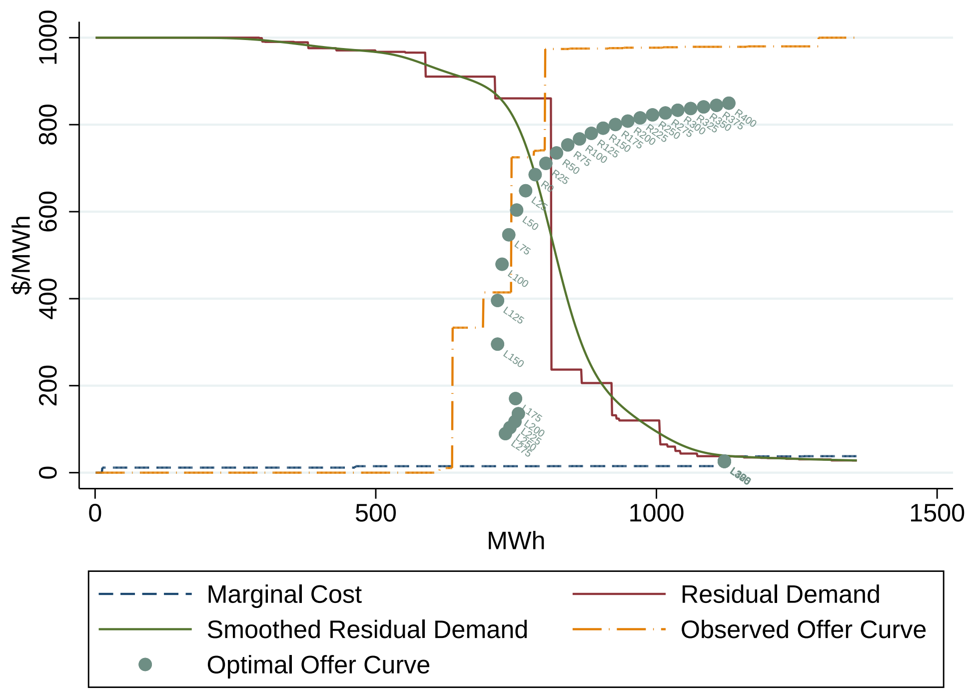
We find that non-monotonicity arises for the majority of peak hours in March 2013 for both Capital Power and TransCanada. Investigating the slope of the *ex-post* optimal offer curve over the 25 MWh shifts of residual demand, we find that the optimal offer curves for Capital Power and TransCanada have at least one segment with a strictly negative slope in 80.35% and 88.27% of hours, respectively. Alternatively, we only find non-monotonicity in 35.78% of hours for ATCO.

As discussed in Section 2, non-montonicity of the *ex-post* optimal offer curve can occur because of multiple local optima, or because the more stringent montonicity condition in (5) fails to hold. To illustrate the former, Figure 6 presents Capital Power's step-wise and smoothed expected residual demand, marginal cost, and its observed and *ex-post* optimal offer curve for March 19, HE 15. The *ex-post* optimal offer curve exhibits three distinct regions, involving high, medium, and low prices. The observed jump in the optimal offer prices associated with the rightward shifts in the residual demand curve of 350 (R350) and 375 (R375) occurs because we move from one set of local optima to another. This is demonstrated in Figure 7 which presents Capital Power's profit function on March 19, HE 15, for the R350 and R375 residual demand curves. For each case, there are two local optima. For the R350 case, the global optimum arises at the higher quantity and

[24]We present graphical examples of TransCanada's and ATCO's *ex-post* optimal offer curves in Appendix D.

[25]The middle section of the residual demand curve is less inelastic in Figure 5 than in Figure 2. This difference can be alleviated by using a smaller kernel smoothing bandwidth. However, as discussed in Appendix C, this enhances the non-monotonicity issues associated with the *ex-post* optimal offer curve.

Figure 5: Capital Power's Observed and Optimal Offer Curves, March 6 2013, HE 21



lower price point. Alternatively, for the R375 case, the global optimum arises at the lower quantity and higher price point reflecting the incentive to withhold output as residual demand increases. This corresponds with the non-monotonic jump to the high-priced region in Figure 6.

Figure 6: Capital Power's Observed and Optimal Offer Curves, March 19 2013, HE15

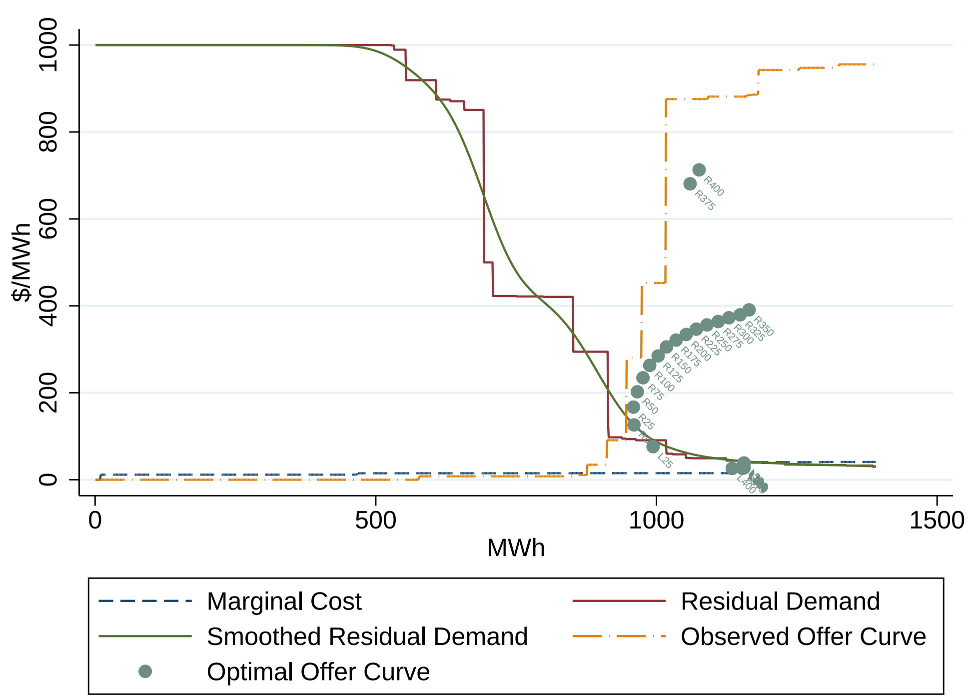
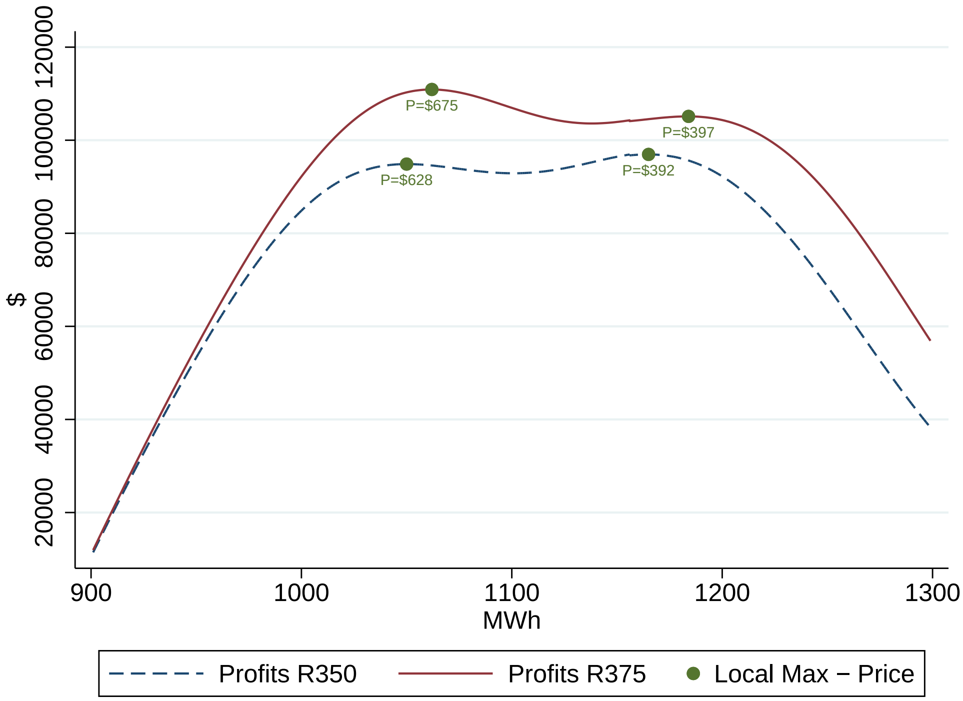


Figure 7: Capital Power's Profit Function, March 19 2013, HE15



Overall, we find that multiple local optima occur in 10.57% of hour-iterations for Capital Power, 28.25% for TransCanada, and 0.54% for ATCO. Further, we find that at least one iteration has multiple local optima in 68.62% of hours for Capital Power, 96.19% for TransCanada, and 10.66% for ATCO in our sample. This demonstrates that for certain firms, multiple equilibria can arise often in our sample.

In Section 2 we demonstrated that the *ex-post* optimal offer curve can be non-monotonic in settings where the profit function does not exhibit multiple optima through violations of condition (5). We demonstrate this case in Figures 8 and 9. Figure 8 presents Capital Power's step-wise and smoothed expected residual demand, marginal cost, and observed and *ex-post* optimal offer curves for March 27, HE 18. The *ex-post* optimal offer curve is non-monotonic. Figure 9 illustrates Capital Power's profit function for different rightward shifts in residual demand, indicating the optimal quantity and price associated with each shift. Notice that the profit functions exhibit a unique local optimum.[26] Consequently, in this hour, the backward bending optimal offer curve is not the result of multiple local optima but rather the curvature of residual demand.

We now investigate whether the firms in our sample are bidding in a manner that differs from the *ex-post* optimal offer curves. Figures 5, 6, and 8 present examples of Capital Power's offer behaviour compared to the *ex-post* optimal offer curves. In these figures, Capital Power submits an offer curve that is steeper than the (often non-monotonic) *ex-post* optimal offer curve. Alternatively, in the same hours for TransCanada and ATCO (illustrated in Appendix D), TransCanada submits offer

[26]The discrete reduction in profits in Figure 9 is the result of a discrete step in the marginal cost curve.

Figure 8: Capital Power's Observed and Optimal Offer Curves, March 27 2013, HE18

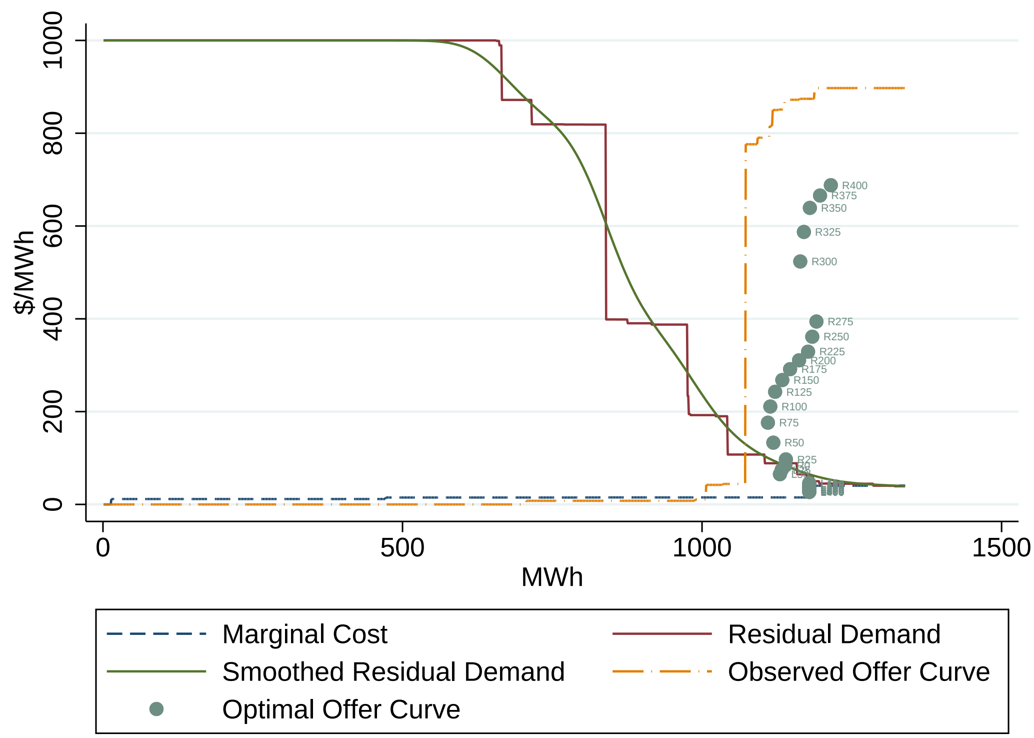
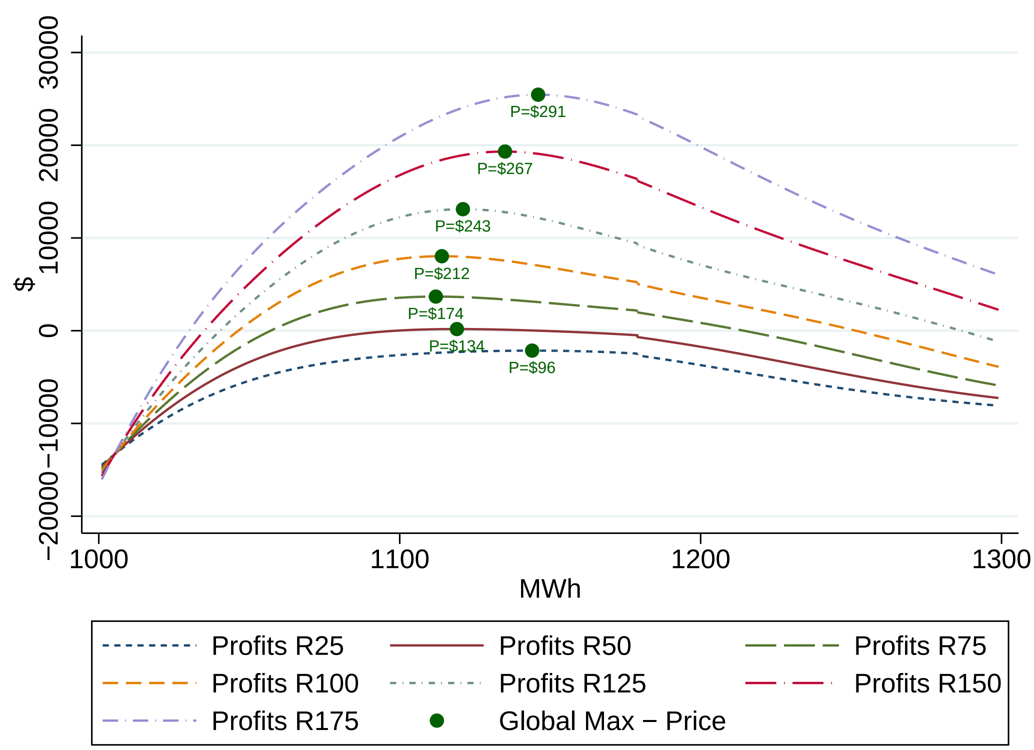


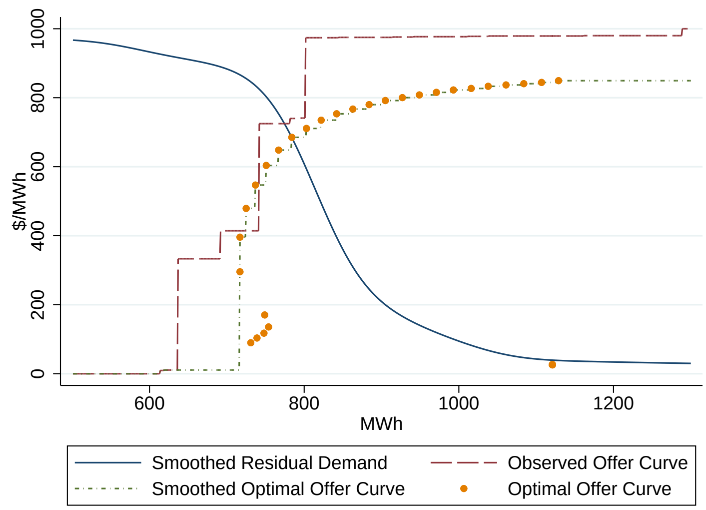
Figure 9: Capital Power Profit Functions, March 27 2013, HE18



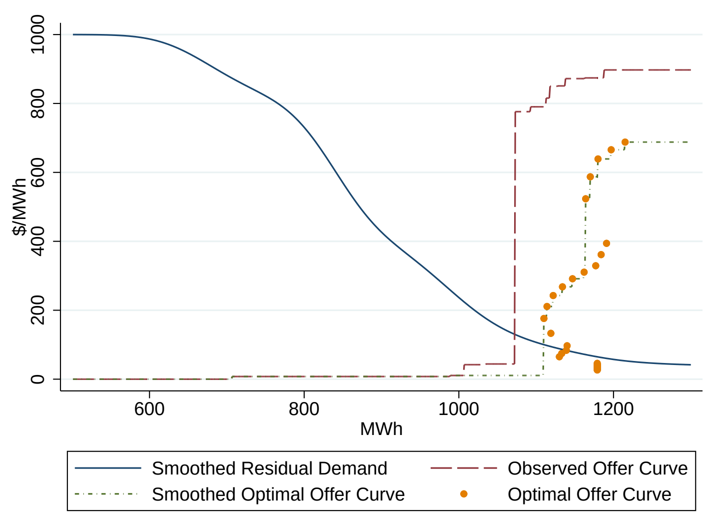
curves that lie both above and below its *ex-post* optimal offer curve, while ATCO tends to submit offer curves that are too aggressive (i.e., lie below) its optimal offer curve. The generality of these patterns is analyzed in detail below.

In order to evaluate if the monotonicity restriction on firms' offer curves is the main driver of the divergence between observed and optimal offer curves, we construct a counterfactual offer curve that reflects the upper envelope of the *ex-post* optimal supply curve. This reflects a smoothed monotonic version of the *ex-post* optimal supply curve.

Figure 10: Capital Power's Observed, Optimal, and Smoothed Optimal Offer Curves



(a) March 6, 2013 HE 21



(b) March 27, 2013 HE 18

Figure 10 presents two examples of the monotonically smoothed *ex-post* optimal offer curve. It is important to note that this offer curve does not pass through all *ex-post* profit-maximizing points. We will investigate if the firms could have achieved the majority of the expected profits by submitting this monotonically smoothed approximation of the optimal offer curve.

For each firm i, we calculate expected variable profits for three cases: (i) the *ex-post* optimal offer curve ($E[\pi_i^{XPO}]$), (ii) actual offer behaviour ($E[\pi_i^{Actual}]$), and (iii) the monotonically smoothed optimal offer curve ($E[\pi_i^{Smoothed}]$). Similarly, we compute expected hourly output (MWhs) under each scenario denoted by $E[q_i^{XPO}], E[q_i^{Actual}]$, and $E[q_i^{Smoothed}]$. For each firm i, we test whether the means of expected hourly variable profits and outputs are equal across these various cases. This entails estimating the following model for both expected profits and outputs:

$$Y_{it}^j - Y_{it}^k \;=\; \alpha_i + \epsilon_{it} \quad \text{for} \quad j,k \in \{XPO, Actual, Smoothed\} \quad \text{with} \quad j \neq k.$$

The null hypothesis $\alpha_i = 0$ allows us to investigate if expected profits and outputs for firm i have the same means across these various benchmarks. The error term ϵ_{it} is robust to heteroskedasticity and within-day serial correlation.[27] Table 2 presents the results of these statistical comparisons.

Table 2: Regression Results

Panel A: Expected Variable Profits			
	$E[\pi^{XPO}] - E[\pi^{Actual}]$	$E[\pi^{XPO}] - E[\pi^{Smoothed}]$	$E[\pi^{Smoothed}] - E[\pi^{Actual}]$
Capital Power	13,090.80***	598.13***	12,492.67***
	(3,622.57)	(90.85)	(3,635.90)
TransCanada	23,320.88***	1,230.03***	22,090.85**
	(6,831.06)	(153.58)	(6,886.65)
ATCO	1,841.39***	227.43***	1,613.96***
	(549.56)	(28.39)	(554.32)

Panel B: Expected Output			
	$E[q^{XPO}] - E[q^{Actual}]$	$E[q^{XPO}] - E[q^{Smoothed}]$	$E[q^{Smoothed}] - E[q^{Actual}]$
Capital Power	142.93***	59.15***	83.77***
	(19.51)	(11.19)	(11.75)
TransCanada	29.61	119.78***	-90.17**
	(20.05)	(12.44)	(18.87)
ATCO	-6.45*	2.75	-9.20**
	(3.54)	(2.74)	(3.41)

Notes. Standard errors are presented in parentheses. The residuals are robust to heteroskedasticity and within-day serial correlation. Statistical significance is represted by $^{*}\,p < 0.10$, $^{**}\,p < 0.05$, $^{***}\,p < 0.01$.

Column 1 in Panel A of Table 2 demonstrates that the *ex-post* optimal and actual variable profits have different means at the 1% level of significance for all three firms. The difference in variable profits are considerable for Capital Power and TransCanada. Compared to the average actual variable profit benchmark (recall Section 4.2 and Table 1), Capital Power and TransCanada could have elevated their average variable profit by 9.9% and 13.3% by utilizing the *ex-post* optimal offer curve. For ATCO, this difference is considerably smaller at 1.9% suggesting that ATCO's

[27] We also considered longer duration serial correlation with 2 to 7 day lagged Newey-West standard errors. The degree of statistical significance is unaffected.

observed offer behaviour was much closer to the *ex-post* optimal offer curve.

Column 2 in Panel A of Table 2 highlights that there are statistically significant differences in the means of the expected variable profits of the often non-monotonic *ex-post* optimal offer curve and its monotonically smoothed approximation; however, these differences are relatively small in magnitude. This illustrates that all three firms could have achieved expected variable profit levels that are close in magnitude to the *ex-post* optimal offer curves. It is important to notice that our monotonic smoothing approach systematically crosses through the *ex-post* optimal offer curve at the lower quantity, higher priced, points and fails to capture the low price, high quantity, points that often drive the non-monotonicity (e.g., see Figure 10). As a result, the smoothed optimal offer curve is able to capture the high profit realizations points of the *ex-post* optimal offer curve.

Column 3 in Panel A demonstrates that the large differences in actual and optimal offer behaviour persist for both Capital Power and TransCanada when compared to the monotonically smoothed *ex-post* optimal offer curves. Taken together, this evidence suggests that the non-monotonicity of the optimal offer curves was not the key constraining factor to allowing the firms to bid in a manner that achieves expected profit levels that are consistent with those that would arise at all *ex-post* unilateral profit-maximizing points in our sample.

Table 2 Panel B compares each firm's output levels across the three benchmarks. Capital Power's actual offer behaviour results in a statistically significant lower level of output compared to both the *ex-post* optimal and monotonically smoothed offer curves. The increase in output under the optimal offer curve is considerable and would represent a 15.0% increase from its average actual output. This reflects the fact that Capital Power systematically submits offer curves that are too steep with large high-priced shelves compared to the *ex-post* optimum and monotonically smoothed optimum (e.g., see Figures 5, 6, and 8). In contrast, for TransCanada, there is no statistically significant difference in actual and optimal output levels, reflecting that TransCanada's actual offer curve lies both above and below its optimal offer curve (e.g., see Figures D.7 and D.9). There is marginally statistically significant evidence that ATCO's actual offer behaviour results in too much output relative to the *ex-post* optimal offer curve, although the difference is small.

For each firm, from Panel B column 2, the monotonically smoothed optimal offer curve results in lower output than the *ex-post* optimal offer curve. This arises because our monotonic smoothing crosses through the *ex-post* optimal offer curve at the higher price, lower quantity, points. As a result, when the *ex-post* optimal offer curve implies a higher quantity, lower price, outcome the monotonically smoothed offer curve yields higher prices and lower quantity to satisfy the monotonicity restriction (e.g., see Figure 10). However, as discussed above, we find that the monotonically smoothed offer curve is able to recover the vast majority of expected variable profits.

Another way to compared across the benchmarks is to consider the expected variable profits over our sample, relative to those that would have been achieved if the firms utilized the *ex-post* profit-maximizing best-response offer curves. For each benchmark $j \in \{Actual, Smoothed\}$, we consider the ratio of the sums of expected profits over our sample by:

$$\text{Percent Achieved}^j \;=\; 100 \times \frac{\sum_{t=1}^{T} \; E[\pi_t^j]}{\sum_{t=1}^{T} \; E[\pi_t^{XPO}]}.$$

Table 3: Percentage of Expected Variable Profits Achieved by Benchmark

	Percent Achieved^{Actual}	Percent Achieved^{Smoothed}
Capital Power	39.11%	97.22%
TransCanada	67.14%	98.27%
ATCO	87.11%	98.41%

Table 3 reinforces our findings above. Over our sample period, Capital Power and TransCanada only achieve approximately 39% and 67% of the potential expected profits compared to the *ex-post* optimal offer curve. ATCO achieves the majority at 87%. Further, for each firm, the monotonically smoothed optimal offer curve earns the vast majority of the expected profits.

Our results demonstrate that an empirical analysis that focuses solely on condition (3) to evaluate if firms are behaving in a manner consistent with expected unilateral profit maximization can lead to incorrect conclusions if the monotonicity requirement on a firm's offer curve is violated under the *ex-post* optimal offer curve. Suppose for example a firm was bidding according to our monotonically smoothed optimal offer curve. Using our method for constructing the smoothed optimal offer curve, for any realization of residual demand, the firm will be operating at a quantity less than or equal to the global optimum quantity for that demand realization. We find that for each firm, in the majority of cases in which the intersection of residual demand and the smoothed optimal offer curve does intersect at the *ex-post* global optimum (because it would violate the monotonicity constraint), the first order condition defined in (3) is positive.[28] Consequently, this may lead a researcher to conclude that the firm could unilaterally increase its profit by increasing its output, suggesting that the firm may be engaging in coordinated behaviour to reduce its production in order to elevate market prices. However, the firm may be acting to maximize its unilateral expected profit subject to the constraint that its submitted offer curve must be monotonically increasing.

5 Conclusions

We utilize data on firms' bidding behaviour in Alberta's wholesale electricity market in 2013 to illustrate the empirical challenges that can arise when using empirical methodologies to investigate firm behaviour. We focus on three large merchant generation firms: Capital Power, TransCanada, and ATCO. We consider empirical methodologies that aim to characterize a firm's unilateral expected profit-maximizing offer curve facing a stochastic residual demand function. Under certain conditions, these approaches collapse down to tracing out the price-quantity pairs that maximize

[28] More generally, the first derivative of the firm's profit function on the monotonically smoothed optimal may not always be positive because profit functions are not globally concave and can exhibit multiple local optima.

a firm's *ex-post* profit function for all possible residual demand curve realizations. We establish necessary and sufficient conditions to ensure that the resulting best-response offer curves are well-behaved and satisfy standard monotonicity conditions imposed in practice.

We find that residual demand functions can be locally convex and highly non-linear in practice. We demonstrate that this can drive a firm's profit function to have multiple local optima. We show that the local convexity of the residual demand function and the multiplicity of local maxima result in backward bending (downward sloping) optimal offer curves in approximately 80%, 88%, and 36% of hours for Capital Power, TransCanada, and ATCO, respectively.

We compare observed behaviour to the optimal offer curves and find that observed bidding behaviour deviates considerably from the optimal benchmark for two of the three firms. We establish a monotonically smoothed approximation of each firms' optimal offer curves to investigate if the observed deviation is driven by the monotonicity restriction imposed in practice. We find that observed behaviour continues to differ from the monotonically smoothed optimal offer curve. In addition, we demonstrate that the monotonic approximation of the optimal offer curve could have recovered the vast majority of expected variable profits (97% - 98%) that would have been achieved under the often non-monotonic optimal offer curves.

Our results demonstrate that empirical approaches that impose the restriction that firms' optimal offer curves must pass through the *ex-post* profit-maximizing price-quantity pairs may lead to incorrect conclusions regarding firm behaviour in practice. While this does not seem to be arising in our setting, such approaches may lead researchers to conclude that firms' are deviating from offer behaviour implied by unilateral expected profit-maximization when in reality they are maximizing their *ex-ante* expected profits subject to monotonicity restrictions imposed in practice.

These findings have important implications for future analyses that evaluate if firms are behaving in a manner that is consistent with unilateral expected profit maximization or whether firms are undertaking some form of coordinated action. The challenges introduced by the highly non-linear residual demand functions may increase going forward as renewable generation with zero marginal cost expands and as peaker natural gas units serve to balance the remaining demand. This emphasizes the need, as noted in Wolak (2000, 2007), to utilize and establish empirical methodologies that account for restrictions imposed on firms' supply functions in practice.

Our analysis suggests several directions for future research. First, our analysis abstracts from dynamic costs, such as ramping and startup costs, that could explain differences between observed and the *ex-post* optimal, static, best response offer curves. While this may alter the exact shape of the optimal best-response offer curve in certain hours, we believe the empirical challenges introduced by the local convexity of the residual demand functions will continue to drive multiple local optima and non-monotonicity concerns. Future research that incorporates these dynamic costs in models that aim to characterize the unilateral expected profit-maximizing offer curves is warranted.[29] Second, the results in the current paper are based on the observation that observed

[29]Using a different methodology and the broader 2013 sample, Brown and Eckert (2019) find that the inclusion of

residual demand curves exhibit shelves and large vertical jumps. Future research should quantify why such residual demand curves would arise in equilibrium. Third, we constructed a counterfactual offer curve that reflects the upper envelope of the *ex-post* optimal supply curve. While we find that this monotonically smoothed offer curve captured the vast majority of expected profits in our setting, a more thorough comparison to the monotonically-constrained unilateral expected profit maximizing offer curve is warranted.[30]

dynamic costs cannot explain the observed deviations in offer behaviour from the *ex-post* optimal best response offer curves for the two firms in our sample.

[30] Wolak (2000, 2010) establish econometric methods that can be utilized to characterize a firm's unilateral expected profit maximizing offer curve subject to bidding constraints imposed in practice.

Appendix

A Theoretical Foundation

We characterize condition (5). Implicitly differentiating (3) with respect to price yields:

$$1 - C''_{it}(\cdot)\, S'_{it}(p) \;=\; \left[\frac{1}{-RD'_{it}(\cdot)}\right]^2 \left\{S'_{it}(p)[-RD'_{it}(\cdot)] - [\,S_{it}(p) - q^f_{it}\,][-RD''_{it}(\cdot)]\right\}$$

$$\Leftrightarrow \quad [1 - C''_{it}(\cdot)\, S'_{it}(p)]\,[\,RD'_{it}(\cdot)\,]^2 \;=\; [\,S_{it}(p) - q^f_{it}\,]RD''_{it}(\cdot) - S'_{it}(p)RD'_{it}(\cdot)$$

$$\Leftrightarrow \quad S'_{it}(p) \;=\; \frac{[\,RD'_{it}(\cdot)\,]^2 - [\,S_{it}(p) - q^f_{it}\,]RD''_{it}(\cdot)}{C''_{it}(\cdot)[\,RD'_{it}(\cdot)\,]^2 - RD'_{it}(\cdot)}. \tag{8}$$

Because cost is weakly convex ($C''_{it}(\cdot) \geq 0$) and residual demand is downward sloping ($RD'_{it}(\cdot) < 0$), (8) implies:

$$S'_{it}(p) \;\overset{\mathrm{s}}{=}\; [\,RD'_{it}(\cdot)\,]^2 - [\,S_{it}(p) - q^f_{it}\,]RD''_{it}(\cdot). \tag{9}$$

Using (3) and that $RD'_{it}(\cdot) < 0$, (9) implies that the supply function is non-decreasing if:

$$S'_{it}(p) \;\overset{\mathrm{s}}{=}\; [\,RD'_{it}(\cdot)\,]^2 + RD'_{it}(\cdot)[\,p - C'_{it}(\cdot)\,]RD''_{it}(\cdot) \;\geq\; 0$$

$$\Leftrightarrow \quad RD'_{it}(\cdot)\,[RD'_{it}(\cdot) + [\,p - C'_{it}(\cdot)\,]RD''_{it}(\cdot)] \;\geq\; 0$$

$$\Leftrightarrow \quad RD'_{it}(\cdot) + [\,p - C'_{it}(\cdot)\,]RD''_{it}(\cdot) \;\leq\; 0.$$

B Expected Residual Demand Formulation

In this section, we provide details about how we formulate each firm's residual demand function which represents market demand net of supply from its rivals. We make use of the stochastic residual demand formulation and analysis in Brown and Eckert (2019). When firms make their bidding decisions, they form expectations about market demand, wind output, and rivals' bidding behaviour. Because wind is priced into the market at \$0/MWh, and both wind output and market demand is uncertain, a central component of uncertainty faced by a firm is the level of market demand net of wind output that is always called upon to supply electricity. For each firm in our sample, we use the following model to estimate net demand level in any given hour t:

$$\text{Net Demand}_{i,t} = \beta_{i,0} + \beta_{i,1}\,\text{Net Demand}_{i,t-4} + \beta_{i,2}\,\text{Net Demand}_{i,t-24} + \beta_{i,3}\,\text{Net Day-Ahead Forecast}_{i,t} + \sum_{j=1}^{24} \alpha_{i,j}\, Hour_j + \sum_{j=1}^{12} \omega_{i,j}\, Month_j + \epsilon_{i,t}$$

where Net Demand_t reflects perfectly price-inelastic market demand minus wind output in period t, Net Demand_{t-4} and Net Demand_{t-24} reflect four and twenty-four hour lagged net demand, Net Day-Ahead Forecast_t is the day-ahead forecast of market demand minus the day-ahead forecasted wind output for hour t, $Hour_j$ and $Month_j$ are hour and month fixed-effects to capture hourly and seasonal variation in net market demand, and ϵ_t is the stochastic residuals. We include four-hour lagged net demand because firms are able to adjust their offer behaviour four hours in advance of market-clearing based on new market-level information (Brown et al., 2018).

We estimate net demand functions for each firm because one firm in our sample (Capital Power) has one wind facility with a maximum capacity of 150 MWs and average output of 53 MWhs. This complicates our analysis because Capital Power faces uncertainty in both its residual demand and its own resource availability. For analytical simplicity, we assume that Capital Power knows its wind output with certainty. We believe this will have a small impact on our analysis because wind represents less then 4% of Capital Power's hourly output on average. Consequently, we estimate two net demand functions, one for ATCO and TransCanada and one for Capital Power. For Capital Power, net demand regressions include market demand minus wind output from its rivals. Our models are estimated using hourly data for all days in 2013.

Table B.1: Net Demand Estimation Results

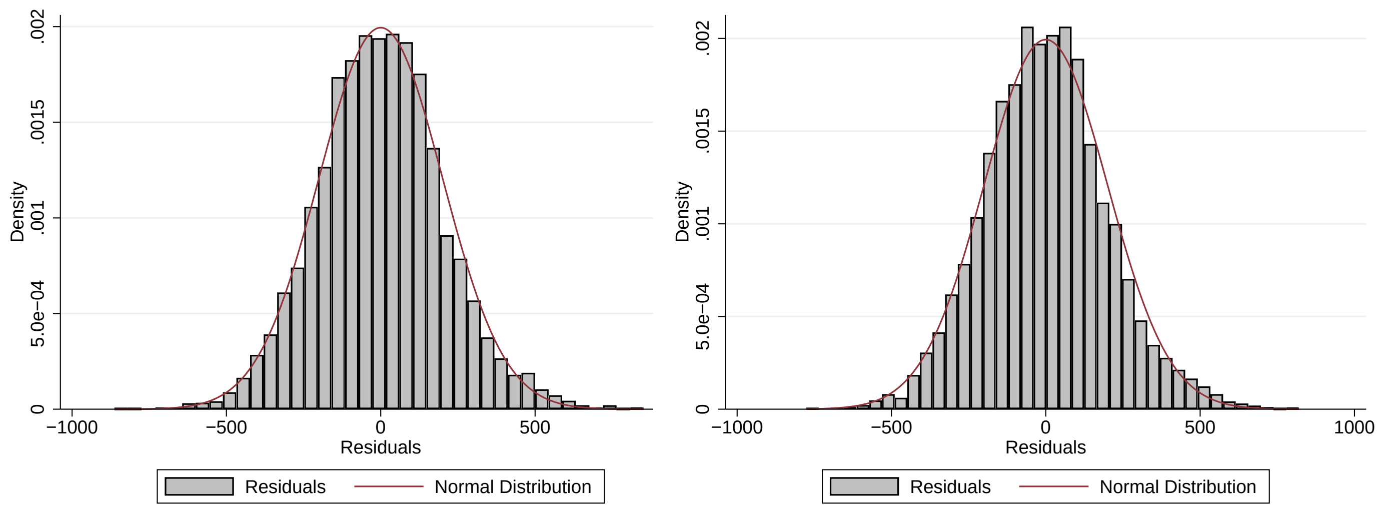
	ATCO & TransCanada	Capital Power
Net Demand$_{t-4}$	0.2306***	0.2313***
	(0.0077)	(0.0076)
Net Demand$_{t-24}$	0.0271***	0.0407***
	(0.0064)	(0.0064)
Net Day-Ahead Forecast$_t$	0.7119***	0.6842***
	(0.0088)	(0.0085)
Constant	-468.2392***	-295.3843***
	(55.3318)	(55.5624)
F-Stat	2,856.83***	2,917.27***
Calendar Controls	Yes	Yes
R-Squared	0.9241	0.9255

Notes. Standard errors are in parentheses. The residuals are robust to heteroskedasticity and 24-hour serial correlation. Statistical significance is represented by * $p < 0.10$, ** $p < 0.05$, *** $p < 0.01$.

Table B.1 presents the results of our net demand estimation. The empirical model above estimates the level of net demand well with an $R^2 = 0.9241$ and $R^2 = 0.9255$. Figure B.1 presents the distribution of the error terms of net demand overlaid with a normal distribution with a mean 0 and standard deviation of 200. This figure demonstrates that a normal distribution $N(0, 200)$ approximates uncertainty well in our model.

For each hour in our sample, we establish a firm's expected residual demand by estimating the expected net demand via the regression above, minus the offer curves submitted by its rival's non-wind generation assets. Subsequently, we consider parallel shifts of ± 400 MWhs in increments of 25 MWhs from the expected residual demand function evaluated at the estimated net demand. The consideration of ± two standard deviations allows us to trace-out the *ex-post* optimal price-quantity pairs for possible residual demand curve realizations with a sufficiently high probability of arising. For example, the probability that the +400 MWhs (R400) iteration will arise equals

Figure B.1: Net Demand Residual Distribution



(a) ATCO and TransCanada

(b) Capital Power

approximately 0.00704 (0.7%).

C Residual Demand Smoothing

We demonstrate that increasing the bandwidth used in smoothing the residual demand curves enhances the degree of non-monotonicity in the *ex-post* optimal offer curves. For illustrative purposes, we focus on the case of Capital Power. Figures C.2 - C.6 replicate the Capital Power figures in Section 4.4, reducing the smoothing bandwidth from 50 MWhs to 30 MWhs.

As is illustrated in the Figures C.2 - C.6, a key effect of decreasing the bandwidth is that the smoothed residual demand curve more closely tracks the expected residual demand curve that is a discontinuous step-function. This results in an increased amount of curvature in the smoothed residual demand function, resulting in more extreme local "shelves" and convex regions. This exacerbates the potential for non-montonicity. For example, over our sample period, using the 30 MWh bandwidth, the percentage of hours with non-monotonic *ex-post* optimal offer curves increases to 90.03% (from 80.35% using a 50 MWh bandwidth). As suggested by the larger jumps in the optimal offer curves and the strengthened local optima in Figure C.4, multiple local optima become a larger concern as the bandwidth is decreased; using the 30 MWh bandwidth, over our sample period, the percentage of hour-iterations with multiple local optima increases from 10.57% to 22.57%, while the percentage of hours in which multiple local optima are observed for at least one iteration increases from 68.62% to 83.87%.

Table C.2 demonstrates that the key conclusions shown in Table 2 persist with a more granular residual demand smoothing parameter for Capital Power.

Figure C.2: Capital Power's Observed and Optimal Offer Curves, March 6 2013, HE 21 - 30 MWh Bandwidth

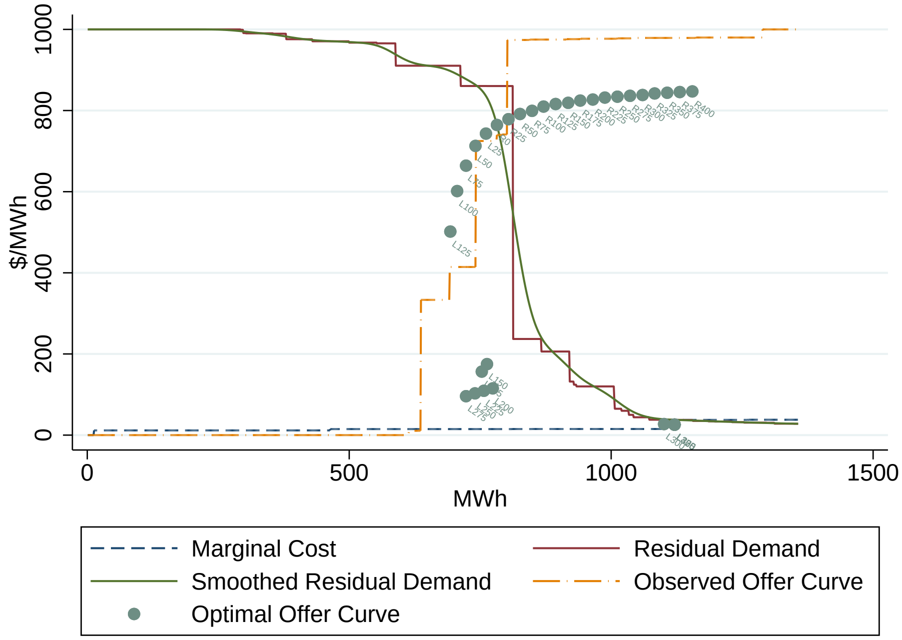


Figure C.3: Capital Power's Observed and Optimal Offer Curves, March 19 2013, HE 15 - 30 MWh Bandwidth

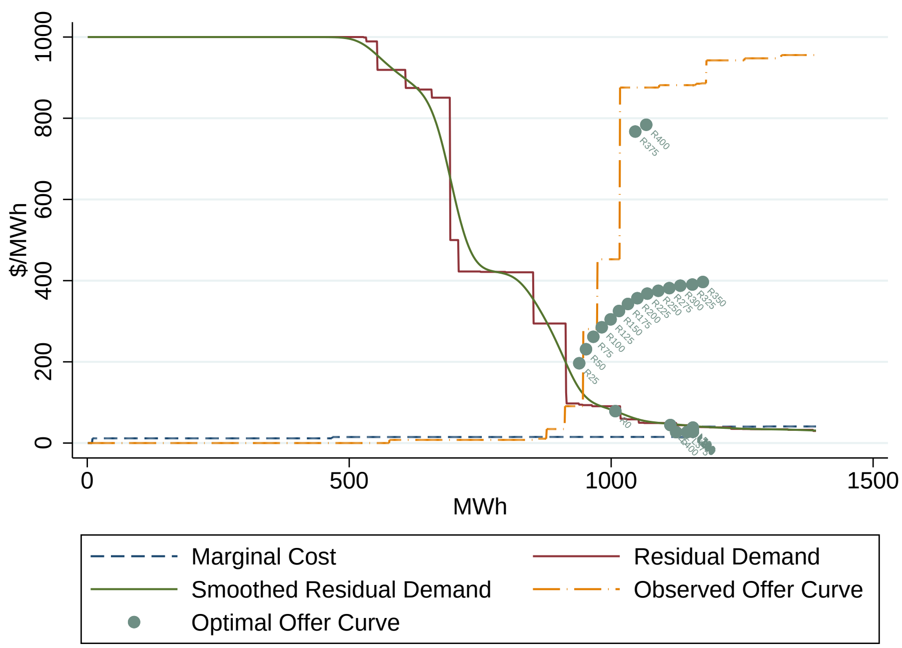


Figure C.4: Capital Power Profit Functions March 19 2013, HE 15 - 30 MWh Bandwidth

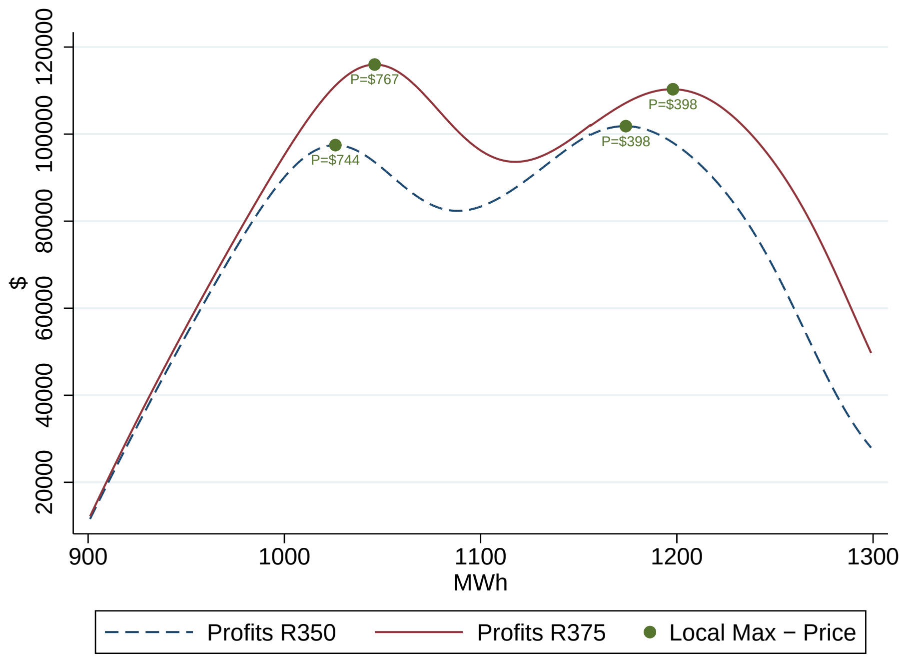


Figure C.5: Capital Power's Observed and Optimal Offer Curves, March 27 2013, HE 18 - 30 MWh Bandwidth

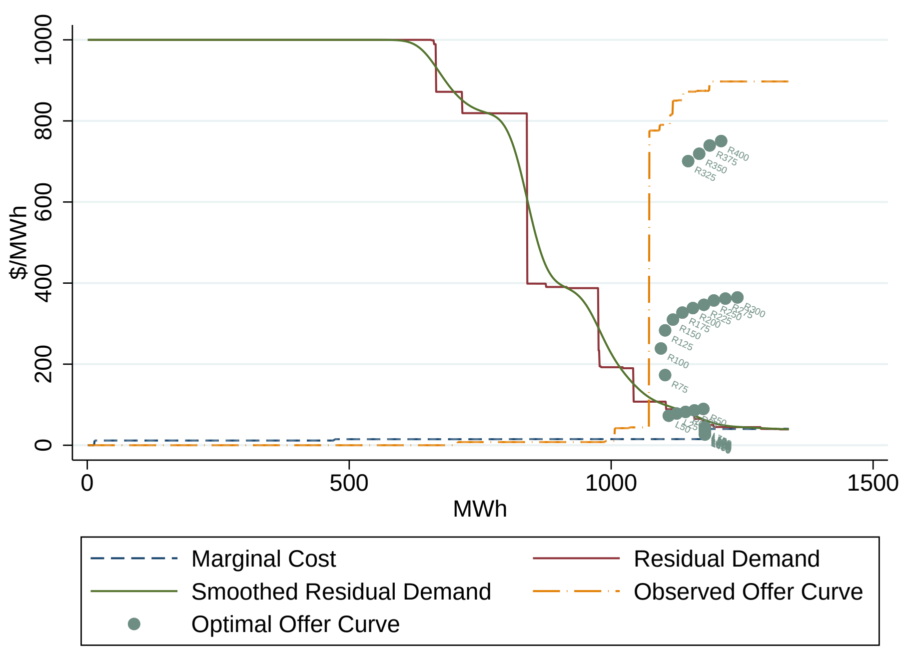


Figure C.6: Capital Power Profit Functions March 27 2013, HE 18 - 30 MWh Bandwidth

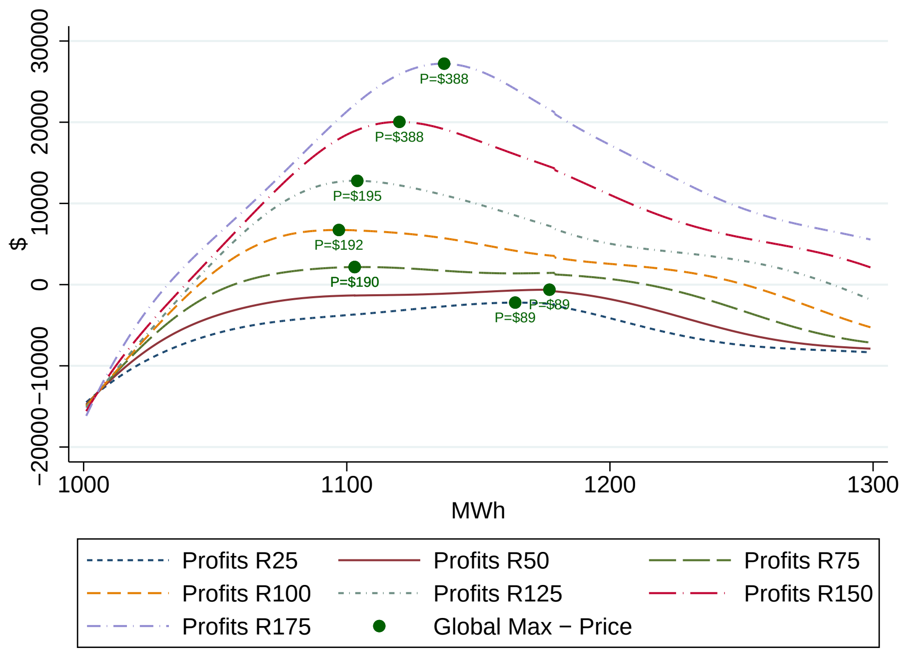


Table C.2: Capital Power Regression Results - 30 MWh Bandwidth

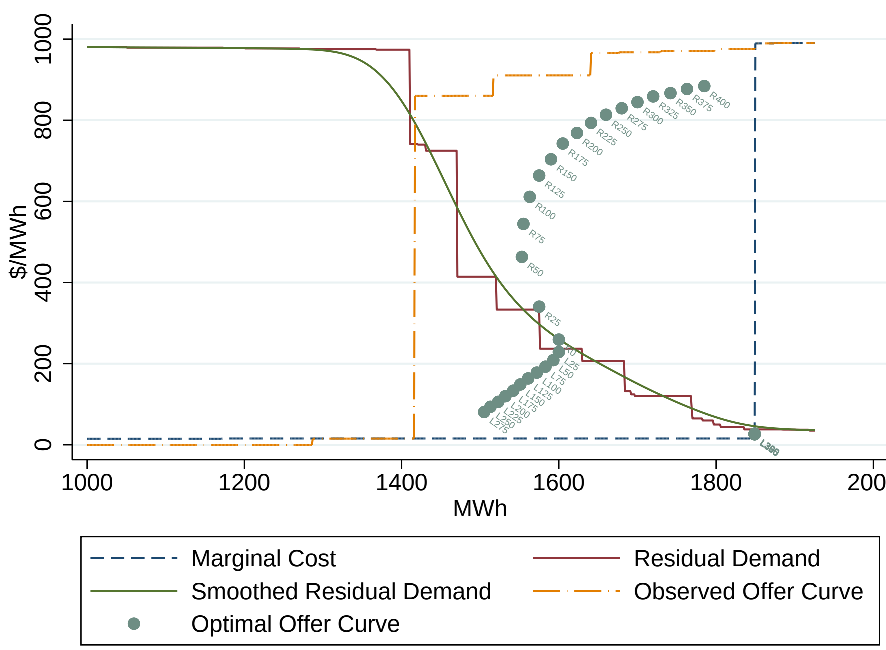
Panel A: Expected Variable Profits		
$\pi^{XPO} - \pi^{Actual}$	$\pi^{XPO} - \pi^{Smoothed}$	$\pi^{Smoothed} - \pi^{Actual}$
14,180.42***	858.63***	13,321.80***
(3,892.65)	(110.04)	(3,901.00)
Panel B: Expected Output		
$q^{XPO} - q^{Actual}$	$q^{XPO} - q^{Smoothed}$	$q^{Smoothed} - q^{Actual}$
142.97***	66.64***	76.33***
(19.27)	(11.44)	(11.49)

Notes. Standard errors are presented in parentheses. The residuals are robust to heteroskedasticity and within-day serial correlation. Statistical significance is represted by $^{*}\, p < 0.10$, $^{**}\, p < 0.05$, $^{***}\, p < 0.01$.

D TransCanada and ATCO Graphical Examples

In this section, we illustrate *ex-post* optimal and observed offer curves for TransCanada and ATCO. Step-wise and smoothed expected residual demand curves for TransCanada, along with observed and optimal offer curves are plotted in Figures D.7, D.8, and D.9 for the three days and hours used in Section 4.4 for Capital Power (March 6, HE 21; March 27, HE 18; and March 19, HE 15). Consistent with Capital Power's results, these figures show that in general, TransCanada's *ex-post* optimal offer curves are infeasible because they violate monotonicity. Further, when TransCanada's observed offer prices differ substantially from the optimal offer curve, it prices above the optimal level in certain hours (e.g., Figure D.7) and below the optimal on others (e.g., Figures D.8 and D.9). This is consistent with the findings in Panel B of Table 2.

Figure D.7: TransCanada's Observed and Optimal Offer Curves, March 6 2013, HE 21



ATCO's residual demand and optimal and observed offer curves for these three illustrative hours are given in Figures D.10, D.11, and D.12. Several key features emerge. First, as shown in Figure D.12, while it is less prevalent, ATCO's optimal offer curve can be non-monotonic. Secondly, visual inspection of observed and optimal offer curves suggest that they are frequently very similar in some cases (see Figure D.10); in other cases optimal offer prices often exceed observed offer prices (see Figures D.11 and D.12), suggesting that ATCO often prices more aggressively than under its unilateral expected profit-maximizing offer curve. This is consistent with the findings in Table 2 where ATCO offers in a manner that is relatively close to the *ex-post* optimal offer curve and when it does it produces in excess of the quantity that would arise under the optimal curve. Third, as shown in Figure D.10, we find that ATCO often operates at its maximum capacity under the observed and optimal offer curve.

Figure D.8: TransCanada's Observed and Optimal Offer Curves, March 27 2013, HE 18

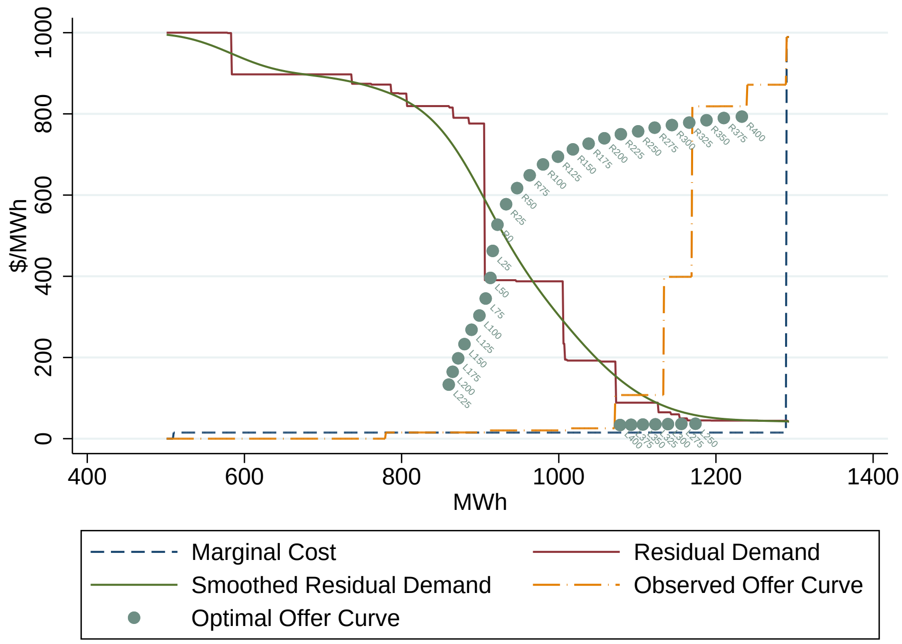


Figure D.9: TransCanada's Observed and Optimal Offer Curves, March 19 2013, HE 15

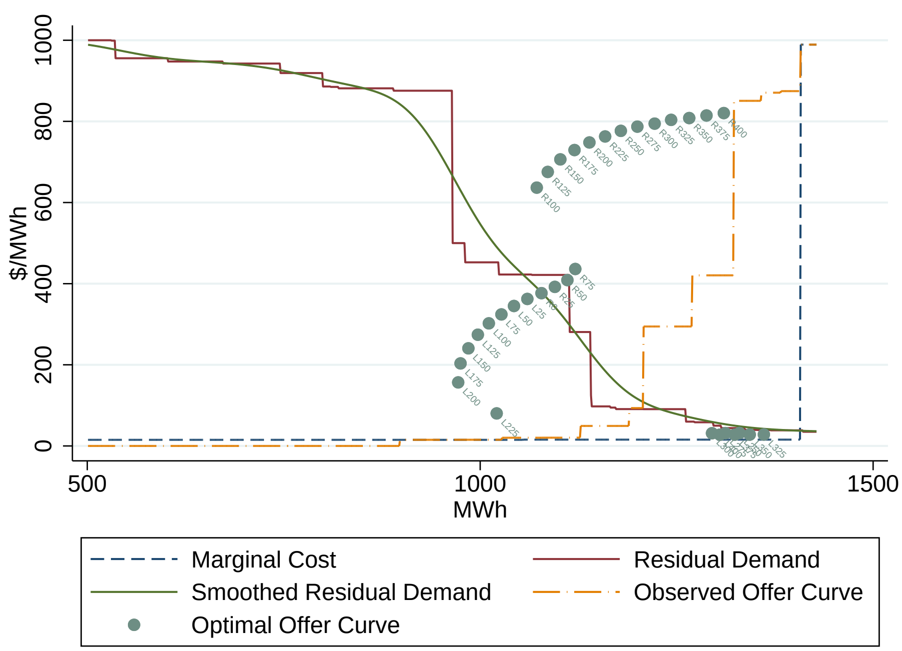


Figure D.10: ATCO's Observed and Optimal Offer Curves, March 6 2013, HE 21

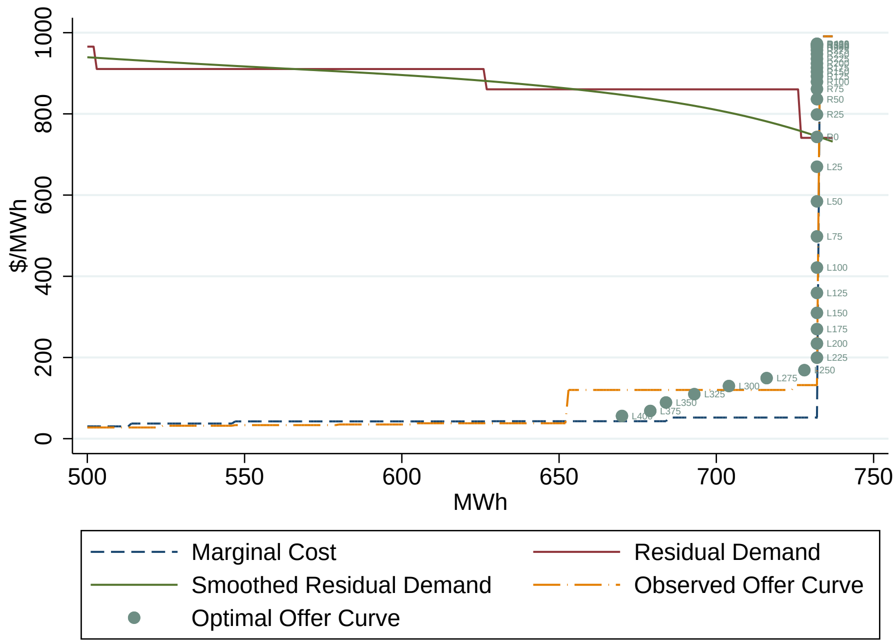


Figure D.11: ATCO's Observed and Optimal Offer Curves, March 27 2013, HE 18

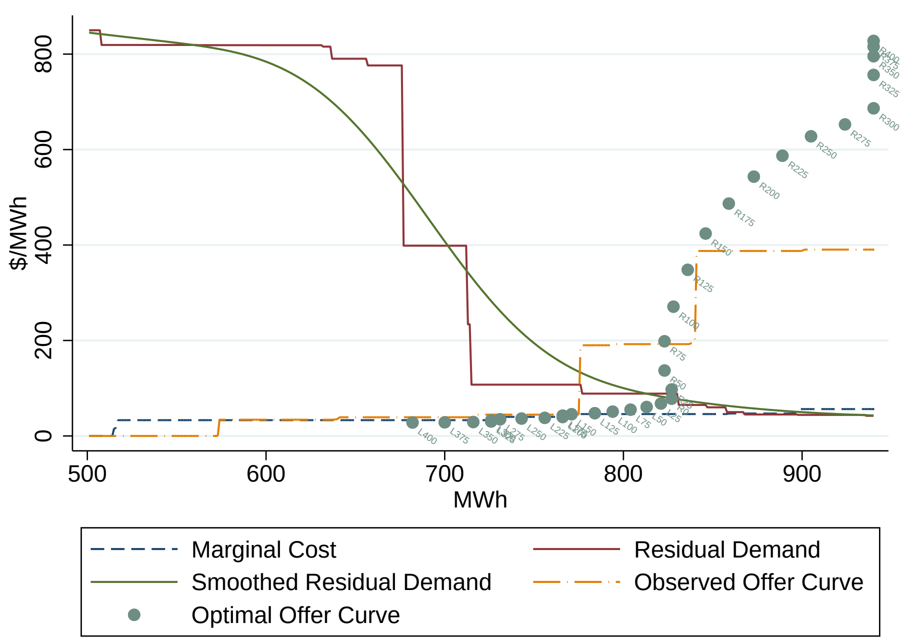
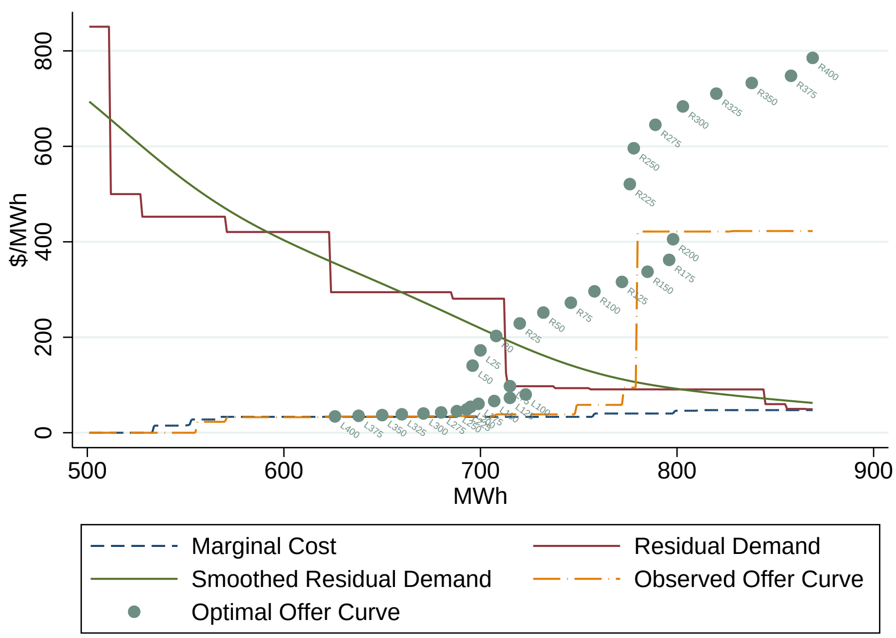


Figure D.12: ATCO's Observed and Optimal Offer Curves, March 19 2013, HE 15



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